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INVESTIGATION OF LEAN MANUFACTURING PRACTICES AND PLANT LAYOUT DESIGN OF A WATER BOTTLING PLANT FROM A SUSTAINABILITY PERSPECTIVE

A THESIS SUBMITTED TO
THE BOARD OF GRADUATE PROGRAMS
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BY

AHMED ZARRAR

IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN SUSTAINABLE ENVIRONMENT AND ENERGY SYSTEMS PROGRAM

SEPTEMBER 2021

Approval of the Board of Graduate Programs

Prof. Dr. Cumali Sabah
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ABSTRACT

INVESTIGATION OF LEAN MANUFACTURING PRACTICES AND PLANT LAYOUT DESIGN OF A WATER BOTTLING PLANT FROM A SUSTAINABILITY PERSPECTIVE

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Companies around the globe are entering an ever-competitive environment, which harbours new challenges that need to be investigated and dealt with. Manufacturers are finding new ways to maximize operational efficiency, improve productivity, and minimize emissions while reducing direct and indirect costs. To achieve these objectives, lean manufacturing is one of the most renowned frameworks used by the industries' tycoons to stay competitive in the global market. The cardinal aim of this research is to conduct detailed flow and operational analysis, and design a lean sustainable production facility layout for purified bottled water production facility. In this research, manufacturing practices and plant layout of the current production facility are investigated from a sustainability perspective to minimize the core eight lean wastes, which in turn increase the net efficiency and improves overall sustainability of the Company X. Two novel approaches were used to create multiple lean layouts for Company X production facility. The classical Systematic Layout Planning (SLP) was modified to incorporate the lean philosophy. The procedural approach named as 'Lean Systematic Layout Planning' (LSLP) was used to develop a layout for the new production facility. Later, pair-wise exchange improvement algorithm was applied to further improve the LSLP based layouts. The proposed production facility layout reduced the total distance travelled by 35.02%, reduced the net material handling cost by 37.05%, and decreased the material handling emissions by 36.86% when compared to the current production facility layout. Furthermore, the proposed model significantly improved inventory, streamlined process, minimized congestion, and enhanced space utilization.

Keywords: Lean manufacturing, Lean layout design, Systematic layout planning, Sustainable layout and material flow, Bottled water production facility

ÖZ

BİR SU ŞİŞELEME FABRİKASININ YALIN İMALAT UYGULAMALARI VE FABRİKA YERLEŞİM TASARIMININ SÜRDÜRÜLEBİLİRLİK BAKIŞ AÇISIYLA İNCELENMESİ

Zarrar, Ahmed
Yüksek Lisans, Sürdürülebilir Çevre ve Enerji Sistemleri
Tez Yöneticisi: Doç. Dr. Volkan Esat
Ortak Tez Yöneticisi: Prof. Dr. Oğuz Solyalı

Eylül 2021, 143 sayfa

İçinde bulunduğumuz çağda, dünyanın dört bir yanındaki şirketler, araştırılması ve ele alınması gereken yeni zorlukları barındıran sürekli bir rekabet ortamına girmektedir. Dünyanın dört bir yanındaki üreticiler, doğrudan ve dolaylı maliyetleri düşürürken operasyonel verimliliği en üst düzeye çıkarmak, üretkenliği artırmak ve emisyonları en aza indirmek için yeni yollar bulmaktadır. Yalın üretim, bu hedeflere ulaşmak için önde gelen sanayi firmaları tarafından küresel pazarda rekabetçi kalmak adına kullanılan, en bilinen yöntemlerden biridir. Bu araştırmanın temel amacı, ayrıntılı bir akış analizi ve operasyonel çözümleme yapmak ve daha sonrasında şirket X şişeleme üretim tesisi için yalın bir sürdürülebilir üretim tesisi yerleşimi tasarlamaktır. Bu araştırmada, temel sekiz yalın atığı en aza indirmek için mevcut üretim tesisinin üretim uygulamaları ve tesis yerleştirimi sürdürülebilirlik bakış açısıyla incelenmekte olup; bu sadece şirket X üretim tesisinin net verimliliğini artırmakla kalmayacak, aynı zamanda sürdürülebilirliğini de iyileştirecektir. Şirket X üretim tesisinde çoklu yalın yerleşimleri oluşturmak için iki yeni yaklaşım kullanıldı. Klasik sistematik yerleşim planlaması (SLP), yalın felsefeyi içerecek şekilde değiştirildi. Yeni üretim tesisi için yerleşim planı geliştirmek amacıyla 'Yalın Sistematik Yerleşim Planlaması' (LSLP) adlı prosedürel yaklaşım kullanıldı. Daha sonra, yerleşimleri daha da iyileştirmek maksadıyla LSLP tabanlı ikili değişim iyileştirme algoritması uygulandı. Önerilen üretim tesisi yerleşimi, mevcut üretim tesisi yerleşimine kıyasla kat edilen toplam mesafeyi %35,02, net malzeme taşıma maliyetini %37,05 ve malzeme taşıma emisyonunu %36,86 azaltmıştır. Ayrıca, önerilen model, envanteri önemli ölçüde iyileştirdi, süreci ve bilgi akışını kolaylaştırdı, tıkanıklığı en aza indirdi ve alan kullanımını daha iyi bir seviyeye getirdi.

Anahtar Kelimeler: Yalın üretim, Yalın yerleşim tasarımı, Sistematik yerleşim planlaması, Sürdürülebilir yerleşim ve malzeme akışı, Su şişeleme üretim tesisi

This thesis is dedicated to Almighty Allah, the most Beneficent and Merciful, for allowing me to complete this study and obtain positive results, and my loving parents. My father, Brig (r) Muhammad Inam Ul Haq and my mother, Rashida Inam. They not only nurtured and raised me to the person I am today but also have been a source of wisdom and inspiration throughout my life. I cannot thank you both enough for everything you have done for me.

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ABBREVIATIONS

AME: Association for Manufacturing Excellence

ARC: Activity Relationship Chart

CBM Conditions Based Maintenance

CORELAP: Computerized Relationship Layout Planning

CRAFT: Computerized Relative Allocation of Facilities Technique

C-VSM: Current Value Stream Map

FLP: facility layout problem (FLP);

F-VSM: Future Value Stream Map

GTA: Graph theoretical approach

H&S health and safety

IoT: Internet of things

JIT: Just in time

LEI: Lean Enterprise Institute

LESAT: lean enterprise self-assessment tool

LM: Lean Manufacturing

MHD: Material handling

MIP: Mixed Integer Programming (MIP)

MULTIPLE: Multi-Floor Facility Layout Problems

PET: Polyethylene terephthalate

QAP: Quadratic Assignment Problems (QAP)

RCM: Row Column Masking

ROC: Rank Order Clustering

SLP systematic layout planning

TCR: Total Closeness Rating

TPM: Total Productive Maintenance

TPS: Toyota production system

VSM: Value stream mapping

CHAPTER 1

INTRODUCTION

1.1 Lean manufacturing background and origin

Japanese automotive industry faced an extreme economic crisis after World War II. Taiichi Ohno, executive vice president of Toyota, noticed the American automotive manufacturers were able to manufacture nearly nine times more than Japanese manufacturers, in the same amount of time by using a larger batch size to accommodate the long setup time (Leyh et al., 2017b). However, the framework of larger batch sizes used by American automotive manufacturers could not be utilized by Toyota due to lower production volume. In 1956, Sakichi Toyoda and Taiichi Ohno pioneered the leaner production system for Toyota Japan to improve production. Leaner production developed by Toyota utilized numerous synchronized steps, techniques and principles for advanced control manufacturing that would *"Do More With Less",* using the minimum amount of resources to achieve the highest quality by mainly focusing on waste reduction, empowering the factory workers, continuous improvement of manufacturing processes and reduction of the net inventory (Osti, 2020; Wilson, 2015) This laid the foundation for Toyota Production System (TPS) published in 1977 (Krafick, 1988). The expression 'lean manufacturing (LM)', first originated in the article "Triumph of the Lean Production System" published by John F. Krafcik in late 1988 at MIT Sloan School of Management (Glass et al., 2016; Leyh et al., 2017a). In this article, John F. Krafcik used this expression to compare the TPS to the western automotive production system. He addressed how production plants following LM can manufacture a wide range of products while maintaining the highest level of quality and productivity

(Krafick, 1988). Later in 1990, the book "The Machine that change the world" by James P. Womack, Daniel Roos and Daniel T. Jones promoted LM over the traditional mass-production system developed by Henry Ford due to its strategic and innovative advantages(Womack et al., 1990). To date, this book is known as one of the most influential economical publication around the globe since it transformed TPS into new philosophy known as lean manufacturing (Glass et al., 2016).

In the current era, authors use the term lean in very diverse ways to illustrate their understanding, opinions and claims. In the existing literature, the term lean is defined as a manufacturing framework/model, set of tools, a set of techniques, a philosophy, a theoretical approach and much more. However, there is an accord that the core aim of LM is to improve productivity and efficiency in any environment by reduction of waste in the origination (Bhamu & Sangwan, 2014).

1.2 Problem statement

'Company X' is a purified bottled water company located in Nicosia TRNC, whose owners are not fully satisfied with their overall performance of the company. The current facility layout of Company X can be seen as a limitation in creating smooth, seamless flow, which could ultimately improve productivity, minimize overhead costs, and minimize emissions. The current layout of the production facility can be categorized into six significant compartments: Type-1 production line, Type-2 production line, Type-3 production line, Type-4 production line, administration, and storage. Since its start in 2007, Company X expanded their production line by placing the departments wherever they seemed fit: depending on the space available, without conducting operational or flow analysis. Due to this, the association in-between departments are not as distinguishable as they ought to be.

Consequently, this leads to increased distance of transport and cost of transportation during production. Furthermore, Company X communication, maintenance or training plans are not up to par. Due to lack of clear communication plans, employees in the production facility are not aware of the daily production orders. This results in inaccurate production quantities stored in inventory, which ultimately leads to an increase in overhead cost and recourse waste. Company X still follows preventative maintenance plans; as a result, in case of breakdown, the entire production is stopped until the issues are resolved. Lastly, there are no training or cross-training programs for the employees currently working at the production facility. Training programs could lower overhead costs and minimize talent waste in the long run. As a result of these shortcomings, Company X is struggling to meet the ever-increasing demand for purified bottled water in TRNC. To stay competitive, Company X needs to develop and evolve by employing new policies such that the net wastes are minimized and the performance is maximized.

Company X has chosen an approach based lean manufacturing concept to address the issues mentioned before. The core aim of this research is to investigate the possible transformation of the current traditional manufacturing framework by making it leaner with a sustainability perspective. To transform the current manufacturing system, Company X has started a collaboration with Kıbrıs Türk Ticaret Odası and Middle East Technical University to develop a new lean manufacturing plant layout and policies for the company.

1.3 Objectives of this study

The core purpose of this study is to develop a sustainable lean plan and layout for Company X, which will minimize the total distance travelled, minimize overhead costs, improve inventory, minimize talent waste, and most importantly derive performance to do more with less.

The objectives of this research are given below:

- Conduct a detailed flow and operational analysis.

- Develop a new leaner layout for Company X.
- Minimize net overhead costs, emissions, and the distance travelled by the products in the production facility.
- Recommend a plan for maintenance and training.

1.4 **Research rationale**

Other than accomplishing the objectives mentioned earlier for Company X, a possible opportunity to develop a framework for lean facility layout planning and implementation is looked into. In future, the developed framework can be utilized by other lean manufacturing-adapting organizations. Using the case study of Company X, this research aims to enhance and widen the horizons of knowledge for other companies of the significant advantages of implementing lean manufacturing with a sustainability perspective. It provides knowledge of a situation in which a current business' operations are examined; after which, possible operational improvements and ideas on how to adopt lean manufacturing concepts are discussed.

Following research questions are derived from the context given above.

- How can lean philosophy be applied to improve operations of late lean adapter?
- Does the layout of production play a crucial role in lean manufacturing?
- What are the key factors that need to be looked into when developing a lean layout for a production facility with particular emphasis on sustainability?

CHAPTER 2

LITERATURE REVIEW

Primarily in the current era Lean manufacturing is a customer-centred approach to improving an organisation's profitability by minimizing the net waste. Anything during production that does not add value to the product or for which customers are not willing to pay is seen as waste (van Assen, 2021). A manufacturer aiming for total lean production recognizes the importance of customer value; hence, they focus on continuously improving the customer value creation process while keeping the net waste to the bare minimum level (Osti, 2020). This can be achieved by streamlining the manufacturing process according to the pace of demand by the customers and continuously focusing on the reduction of the period between order placement; by the customer and order delivery; to the customer by minimizing everything that consumes manufacturers resources such as time, finances and man power (Shah & Ward, 2003). In the current era, lean is also seen as a journey that adds value to the manufacturer by reducing the number of net defects and other wastages; according to lean philosophy, the best way to maximize profits in an organization is to reduce waste which is directly related to costs such as unnecessary activities, overburdening of equipment & man power or variation in quality during production (Malavasi, 2017).

2.1.1 Types of waste

There are mainly three categories of wastes in lean manufacturing literature, i.e., Muda, Muri and Mura. These three types of waste categories are often known as the three ‘Mu’ and are interlinked. One type of waste can often lead to another type of waste, as shown in Figure 2.1.

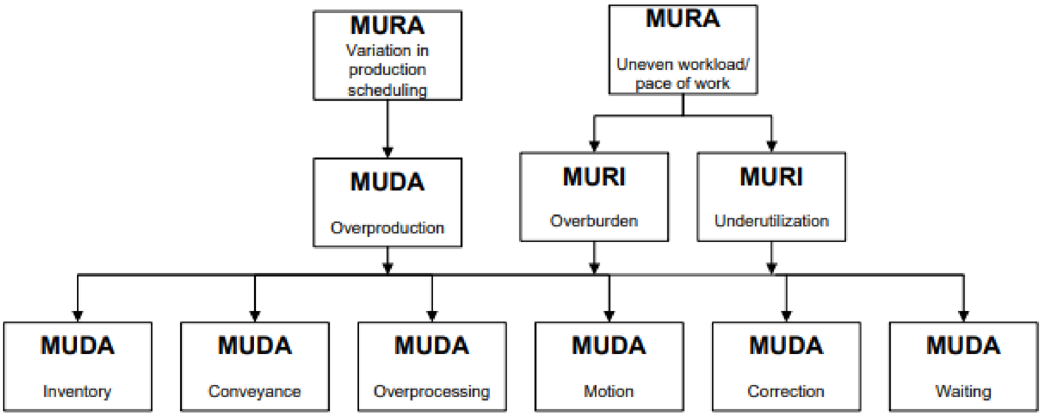


Figure 2.1. The three Mu (Pienkowski, 2014)

1. **Muda:** Muda is a Japanese term that means waste or uselessness. It is characterized as unnecessary activities which consume time, money and resources without adding value to the customer. The sole purpose of identifying Muda is to distinguish which steps are essential to the product and nonessential. Furthermore, if those nonessential can be eliminated or minimized (Osti, 2020).
2. **Muri:** Muri is a Japanese term that means overburden or unreasonableness. It is characterized as waste caused due to overutilization of manufacturing equipment, human resources such as workforce, or facility, which reduces their capacity to perform in the long term. In the literature, Muri is often seen as the exact opposite of overburden, i.e. underutilization of manufacturing equipment, human resources or facility, since this can increase the idle time. There are mainly three types of Muri, i.e. Poorly organized workstations, lack of standardized work and, lastly variation in production volume (Osti, 2020; Pienkowski, 2014).

3. **Mura:** Mura is a Japanese term that means variation or unevenness. It is characterized as waste caused due to unordinary variation in production scheduling or variation in pace of work. Typically, companies want to manufacture in large batch sizes to maximize key resource use while minimizing costs. However, to accommodate the variation in customer demands, companies tend to keep a buffer stock to tackle these variations. Mura can lead to *"bull-whip"* effect. This variation in production demand can lead to significant changes in batch production, which ultimately causes excess inventory. Furthermore, it can lead to an intense load on workers and machinery at unexpected times (Pienkowski, 2014).

There are mainly eight types of wastes in the production facility in current Lean literature, shown in Figure 2.2. These wastes also lie under the category of Muda discussed before in this section. An organization aiming towards lean manufacturing needs to prevent and minimize these types of wastes. The application of lean techniques in an organization has a number of advantages: improved quality of production, decreased number of defects, better space allocation, improved H&S, and even lower emissions. However, detecting these wastes is a daunting task which is discussed in the following sections of this study.

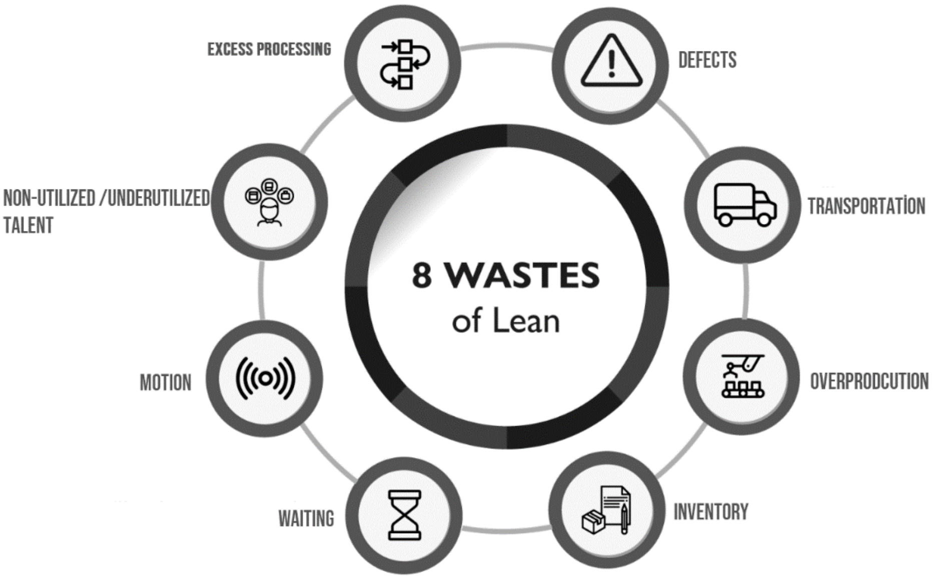


Figure 2.2. Eight Wastes of lean

Defects: Production of defective goods which do not meet clients' specifications may require repair or remanufacturing of replacement goods, which is a significant type of waste in the production facility. Defects tend to slow down the net production and tentatively increase lead time, causing financial strain and overburden human resources. It is essential for manufacturing firms to identify the root causes of defects and eliminate them as soon as they arise (Dilanthi, 2015; Osti, 2020; Wibowo et al., 2018).

Transportation: During manufacturing of the product, raw materials, components and finished goods are transported in-between different departments and workstations. Transportation does not add value to the finished good but is often indispensable (Osti, 2020). Excess transportation is by far an enormous waste in lean manufacturing since it leads to financial strain , an increase cycle time, and leads to H&S risks, increase carbon footprint, cause congestion and lastly cause defects and loss in quality of production (Osti, 2020; Pereira, 2009; Wibowo et al., 2018).

Overproduction: Excess/excessive production of goods more than the customer's internal or external demands or production of goods way before they are required

(McGivern & Stiber, 2004). It can lead to numerous other wastes such as the unnecessary increase in inventory, excess transportation, excess motion and lastly, risk of obsolescence (Osti, 2020; Pereira, 2009). However, it is compulsory even for lean manufacturers to intentionally manufacture an extra supply of semi-finished or finished goods to meet the demand (McGivern & Stiber, 2004; Pereira, 2009).

Inventory: It refers to having excess and unnecessarily high level of semi-finished and finished goods and raw materials. This type of waste can lead to further use of space, finances and even increases the rate of defects in manufacturing plant. (McGivern & Stiber, 2004; Pereira, 2009). According to lean principles, the net inventory and emergency stocks should be as low as possible (Saheed, 2010).

Waiting: It refers to the time frame when production is at a halt, and the workers and the machines are idle. This waste's core reasons are bottlenecks, lack of raw materials, waiting for correct information, and inefficient production flow. (Osti, 2020; Pereira, 2009). Waiting waste can result in increased labour costs and an increase in depreciation costs (McGivern & Stiber, 2004).

Motion: It refers to the movement of employees and equipment that does not add value to the final product and diverts them from the actual processing, which adds value to the product (Osti, 2020). One such example of motion waste is when employees on the factory floor move around to look for tools (McGivern & Stiber, 2004). Motion is known as productivity killer since it not only increases the net cost and time but also can lead to H&S inside the production facility (Simboli et al., 2014)

Excess processing: It is defined as unintentionally doing more work and operations than the customer's requirement to increase the quality or features of the product being manufactured. One such example of over-processing is applying additional finishing processes such as polishing, which the customer does not require (Simboli et al., 2014).

Non-utilized/Underutilized talent. It is the eighth type of waste which is very recently added to the lean waste list**.** In the business and strategy development, the organisation that does not empower their highly capable and talented employees introduces an overall waste in production. It acts as a barrier in sharing ideas and skills, which can increase production efficiency and perform as a learning platform for the employees and employers (Wibowo et al., 2018).

2.2 Lean manufacturing five key principles

James P. Womack and Daniel T. Jones, founders of the Lean Enterprise Institute (LEI) defined *'Principles of Lean'* to systematically identify and eliminate the wastes and inefficiencies in an organization (Mark Crawford, 2016). There are five steps in the identification cycle aiming towards continuous improvement. Figure 2.3 illustrates the five steps of the process developed by LEI.

Figure 2.3. Five key steps for lean manufacturing (Mark Crawford, 2016)

2.2.1 Identify value

The slogan of “Customer first can term the core objective of lean”. Identifying the product's value is the starting point for lean implementation in an organization (Malavasi, 2017). Value is customers’ need for the product being produced. For example, what price point is the customer satisfied at? What is the timeframe for manufacturing and delivery? What is the exact specification the customer is looking for? (Mark Crawford, 2016). Several techniques and tools are used for understanding customers’ precise needs, such as questioners, interviews, surveys etc.

2.2.2 Value Stream Mapping

The second step is mapping the value stream or all the steps and processes required to convert raw materials into final product/product families, ready and delivered to the customer (Mark Crawford, 2016; Osti, 2020). Value Stream Mapping (VSM) identifies value-added and non-value added activities through material flow monitoring, wastes monitoring and manpower monitoring (Hebbar et al., 2015) . If not done efficiently, it acts as a barrier in identifying wastes and inaccuracies, which in turn can result in hindrance and complications when developing models to overcome current issues of the manufacturing plant (Che Ani et al., 2014). VSM highlights opportunities to improve and eliminate waste through evaluation, execution and implementation of lean approaches. This in turn not only drives performance, set goals for new production plant but also reduces non-value added processes (Pettersen, 2009).

2.2.2.1 How to use a value stream map?

For effective use of value stream mapping, it is not enough to draw one map of the entire current state of the organization. Rother & Shook (2003) recommended four critical stages in the development and use of VSM, as shown in Figure 2.4 (Rother & Shook, 2003).

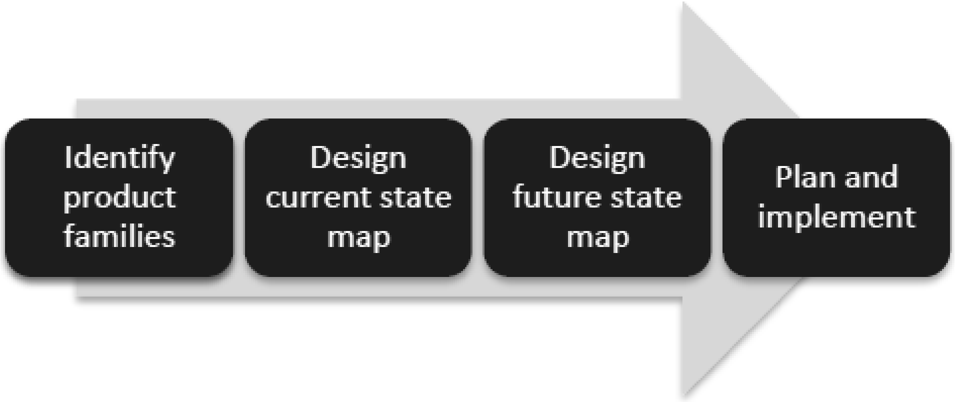


Figure 2.4. Steps for forming VSM (Rother & Shook, 2003)

The first step is the identification of product families (Rother & Shook, 2003). Product family is the division of products into numerous groups that follow identical processes and steps during production or utilize the same resources. Identification of part families can be made using numerous ways such as rank order clustering, row and column masking, similarity coefficient and bond energy (Bastas, 2020). Identification of part families is discussed in detail in the following chapters of this thesis. When forming VSM, it is recommended to focus on one single product in the product family for the purpose of simplifying VSM since a single product can illustrate the generalized steps that what will happen in the entire family (Erlach, 2013).

After forming the product family, the second step is the creation of the current state map. This map should illustrate every operation and step as accurately as possible since it is later utilized for the design of future state map. It is recommended to use numerous symbols from literature consistently (Erlach, 2013). Figure 5 shows the example of symbols used in the current state and future map whereas Figure 6 illustrates a basic example of the current state map of a single product in the product family.

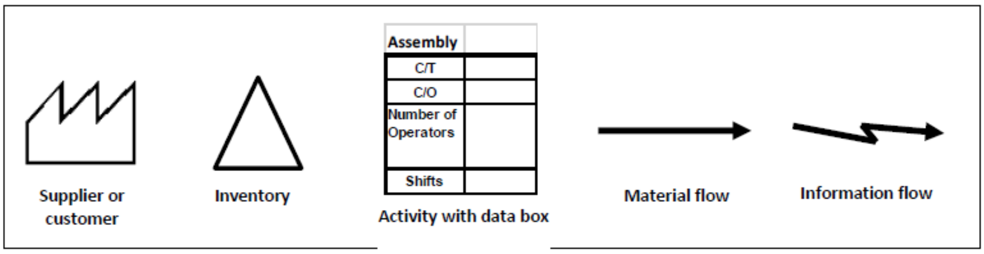


Figure 2.5. Symbols typically used in VSM (Kamne & Sjöberg, 2015)

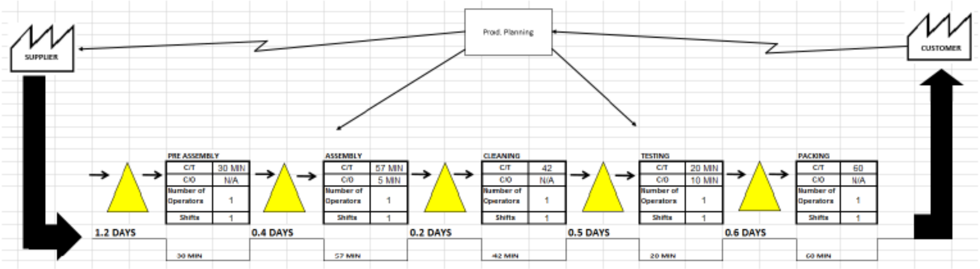


Figure 2.6. Sample VSM (Kamne & Sjöberg, 2015)

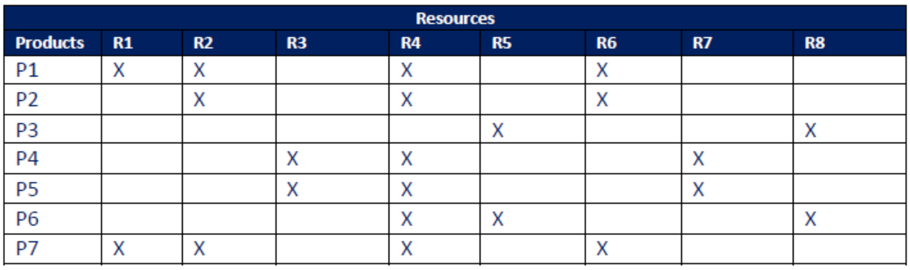
After the completion of the current VSM, the next stage is to develop the future state map of the organization (Rother & Shook, 2003). The core purpose of developing the future state map is to display a tentative future scenario where the current state map identifies the initial wastes and removes them without compromising the quality of value-adding activities. This future state map acts as the guide for the organization to reach the ultimate goal of ideal lean state (Emiliani & Stec, 2004).

The last stage of the use of VSM is to develop a plan for implementing the suggested future state plan (Rother & Shook, 2003). In the majority of the organizations, the net resources such as finances, land, and human resources are insufficient to implement all the proposed changes at once. Rother & Shook strongly advised creating a step-wise implementation plan that can be implemented in a specific sequence, i.e. starting with implementing minor process and operation changes and leading to bigger ones once the current ones are completed (Rother & Shook, 2003).

2.2.2.2 Part family matrix

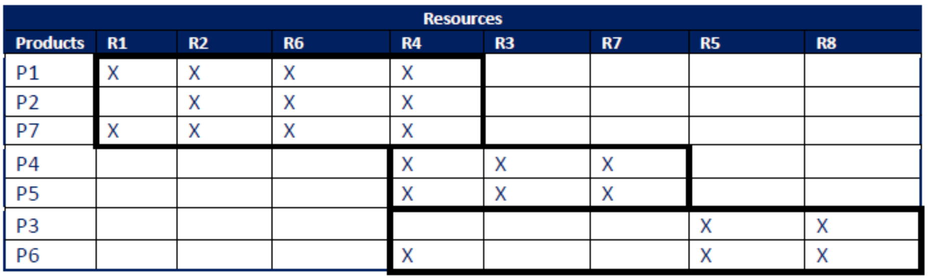
Part family categorises products into numerous groups that follow identical processes/steps or utilize the same resources in a manufacturing plant (Erlach, 2013). One of the main reasons for categorization is to reduce the overall complexity of the current value stream map and future value stream map. Furthermore, this division also assures that the relevant products are investigated according to customers' perspectives. (Kamne & Sjöberg, 2015). This categorization of products into groups known as a management philosophy is 'Group technology'. Cellular Manufacturing (CM) is an application of GT, that that is based on grouping machines based on the parts manufactured on those machines.(Bastas, 2020)

Rother & Shook used a product family matrix, and listed all the products in the vertical axis and the resources used on the horizontal axis. Next, every part that utilizes the resources was marked in the corresponding cells, as shown in Figure 2.7. Later products are grouped into families after analysing the similarities between them, as shown in Figure 2.8 (Kamne & Sjöberg, 2015).



	Resources							
Products	R1	R2	R3	R4	R5	R6	R7	R8
P1	X	X		X		X		
P2		X		X		X		
P3					X			X
P4			X	X			X	
P5			X	X			X	
P6				X	X			X
P7	X	X		X		X		

Figure 2.7. Initial part resources matrix



	Resources							
Products	R1	R2	R6	R4	R3	R7	R5	R8
P1	X	X	X	X				
P2		X	X	X				
P7	X	X	X	X				
P4				X	X	X		
P5				X	X	X		
P3							X	X
P6				X			X	X

Figure 2.8. Products divided into product families

There are a number of other methods to categorise products into groups/product families, such as rank order clustering, row and column masking, similarity coefficient and bond energy (Bastas, 2020). Rank order clustering is used for Company X and is discussed in detail in Chapter 4.

2.2.3 Create flow

After the creation of the current state VSM and future state VSM, the next phase is of creating a flow of lean thinking as advised by future state VSM. This stage makes sure that the course of moving towards lean is followed efficiently without any major hurdles such as bottlenecks, interpretation or delays (Mark Crawford, 2016; Osti, 2020). In order to develop and implement lean culture in an organization, by far the most crucial step is to break down silo thinking and to make sure that all departments are on an accord to move towards lean culture. This can be one of the biggest hurdles when moving towards lean manufacturing. Studies show that after completing this stage, an organization can see as much as 50% improvement in overall productivity and efficiency (Mark Crawford, 2016).

2.2.4 Establishing pull

Pull-production is strategically one of the most critical principle in lean manufacturing. In pull production, orders are based on demand from the customers rather than a forecast of demand. Successive operations are carried out only when needed or requested by the next stage. It minimizes the work in progress and the net inventory of goods (Leal et al., 2012). Figure 2.9 shows the basic pull system at an organization.

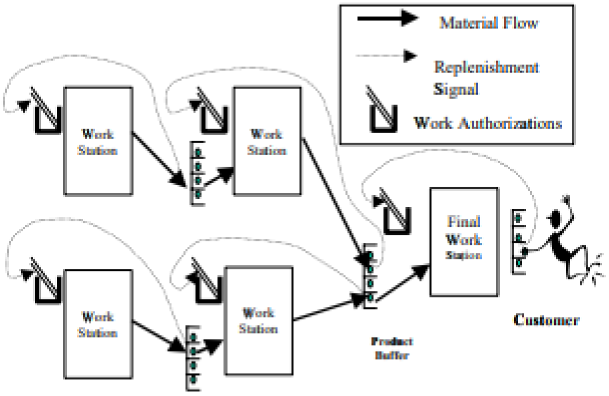


Figure 2.9. Pull Production control(Yingling et al., 2000)

In normal push production, there are extra added costs due to the unsold products in the inventory (Spearman & Zazanis, 1992). As the production is untracked and, excess unsold products are kept in stock, it leads to improper tracking, which not only results in improper quantity of material supplied to manufacturer but also in the schedule alteration. Pull-system is essential for the implementation of Just in Time (JIT). JIT requires efficient, seamless transportation of raw materials and communication in-between different departments, machines within the department and in-between the manufacturer and the customers (Shaaban et al., 2013). In order for the successful implementation of the Pull-system, it is essential that there is effective coordination and accurate information flow within the organization. Since inaccurate information flow could lead to financial loss (Mark Crawford, 2016; Osti, 2020).

2.2.5 Seek perfection

Lean system is not a static system; its foundation is based on '*Continuous improvement'*, also known as Kaizen in Japanese. The aim of the aforementioned principles is of development and implementation of lean philosophy in an organization whereas, this principle aims to continuously improve the developed plan to reach perfection (Osti, 2020). In order to reach the maximum level of attainable perfection, it is essential that all the employees: from top management to the floor worker, need a change in mentality to continuously make changes and strive for perfection (Malavasi, 2017).

2.3 Core pillars lean manufacturing

Lean manufacturing is an integrated system that utilizes numerous managerial practices and sequential, highly integrated elements. In this section most common tools, i.e. Pillars of Lean Manufacturing are briefly discussed.

2.3.1 Just in Time (JIT)

Just in time (JIT) is the concept of conducting operations as soon as they are requested. JIT require companies to have the amount of part at the right time and conducting a sequence of operations as soon as they are requested. JIT increases the competitiveness of manufacturers by reducing lead time and the net inventory, but it needs constant adjusting of production flows to improve efficiency. This adjustment is based on the frequent communication within very small time spans between different functional departments. (Fullerton & McWatters, 2001).

2.3.2 Kaizen

Kaizen refers to continuous improvement in an organization. The term Kaizen is derived from two Japanese words, “Kai” and “Zen”. *‘Kai’* means change whereas, *‘zen’* means for better. In order to effectively apply Kaizen, it is essential for all members of the department to be on an accord and to be ready to do everything in their potential in small incremental steps, rather than few radical changes. This process of small incremental change allows both employers and employees to comfortably adapt to the changes. There are three factors that play a vital role in the fruitful application of Kaizen, i.e. Training of employees, Visual management and the role played by the top management/supervisors (Marof & Mahmud, 2016).

2.3.3 Kanban

The term Kanban is derived from two Japanese words “Kahn” and “bahn” which literally means “visible record” (Rahman et al., 2013). In Kanban methodology, visual Kanban cards are used as way for signal communication to update both internal and external affairs of the production plant. Production only starts when a Kanban signal is sent from the external affair i.e. Customers, to the internal affairs i.e. Manufacturing facility. Inside the manufacturing plant Kanban cards are used to inform and update the manufacturing team of the current state of production such as orders/task that are in que, are in process and are completed.

In the current era of IoT and industry 4.0, Traditional Kanban's synergy coupled pull system to gain the competitive edge. Nadia et al. developed an algorithm that carries out real-time processing using machine learning (Deep Learning Networks) (Belu et al., 2018). Self-harvesting sensors are used for real-time data acquisition, whereas ad hoc and radio networks for the data transfer and communication for generating virtual production e-Kanban tickets as soon as the demand is generated to improve the efficiency of the production. The figure below shows the proposed single-channel Kanban solution by Nadia et al. (Belu et al., 2018).

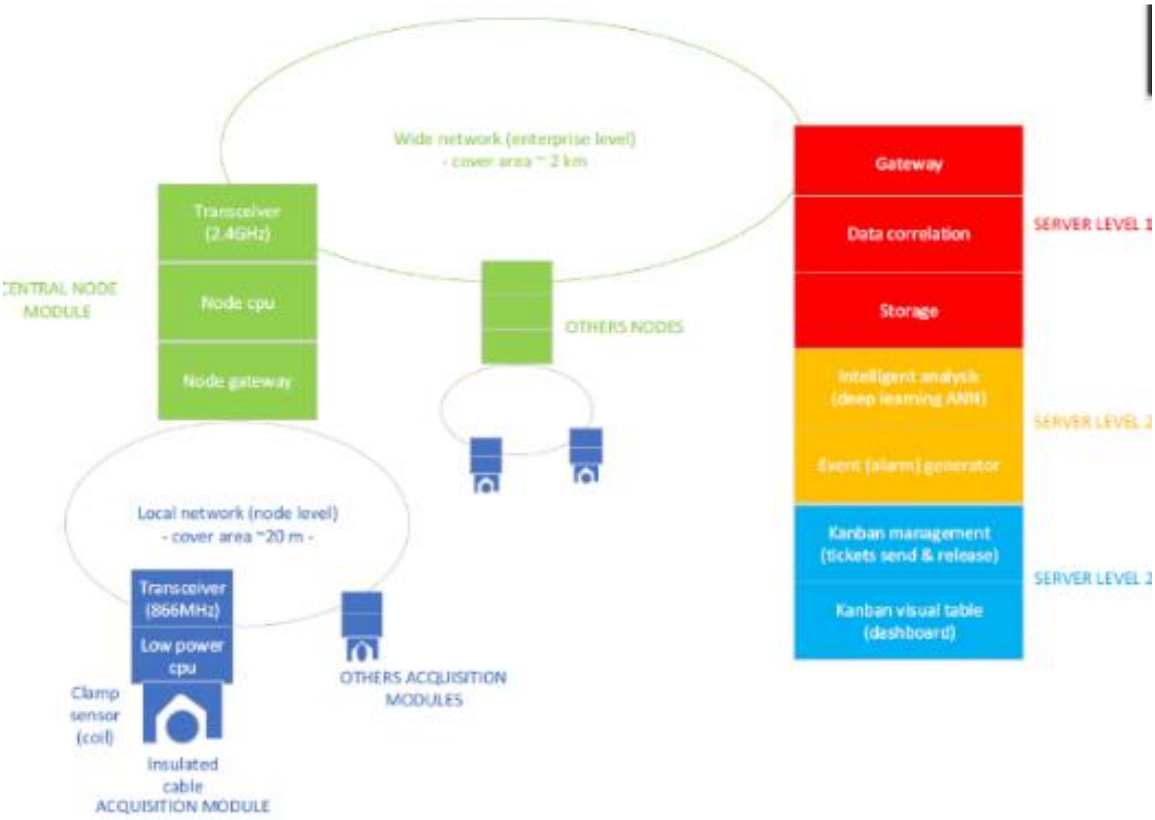


Figure 2.10. Single channel Kanban production proposed by Nadia et al.

The proposed solution gathered the real time data from numerous clamp sensors (nodes), which were sent to the central node module using 866 MHz transceivers. The central node module sent the data to the company servers roughly 2 km away using a 2.4 GHz transceiver. The data collected is analysed using Artificial Neural

Network and Deep Learning which later generates e-Kanban tickets based on the data collected by the clamp sensors. These virtual Kanban tickets are automatically uploaded to the e-Kanban visual table for the working staff. Automatically generated e-Kanban tickets perform as a visual representation for the tasks which are in progress, are completed and/or need to be done by the working staff at the production plant. This promotes not only efficient process control but also promotes active communication in between departments (Belu et al., 2018).

2.3.4 5s and visual management

5s is one of the most widely used tool is design and implementation of lean manufacturing. Its core purpose is to develop a clean, well-organized workspace, while decreasing the net waste of finance, time and space (Osti, 2020). 5s is derived from five Japanese words, which start with the letter S.

1- **Seiri** (Sort): It is the process of elimination of unnecessary tools and machinery that are not used during production.
2- **Seiton** (Set in order): It is the logical order of placement of the tools in predefined locations.
3- Sesion (shine): It is the process of maintaining and cleaning the tools and works space.
4- Seiketsu (Standardize): It is the establishment of simple rules for placement and storage of tools, using visual aid and training of employees and employers.
5- Shituske (Sustain): It is the evaluation and continuous improvement of the previously mentioned four steps.

One of the core purposes of 5s is to develop a strategically safe, efficient and visual workspace. However, this requires the use of simple and to understand visual markers. 5s and Visual management go hand in hand and hence should be implemented together, after the training of the employers and employees. (Kamne & Sjöberg, 2015).

2.3.5 Total Productive Maintenance (TPM)

Lean philosophy is expanding at an immense pace in the manufacturing sector. There is an expanding acknowledgement that lean maintenance should not be seen, distinctively in a limited operational setting: dealing with only equipment failures after the failure has occurred. Rather, it should be seen as the core foundation for dealing with technical, commercial and financial strategy to gain the maximum benefit (Baluch et al., 2012). Unexpected breakdowns can result in not only significant financial losses to the organization but also significantly increases the net waste of non-financial resources, such as a decrease in quality of production and an increase in defects (Arslankaya & Atay, 2015). It is essential for organizations to employ lean maintenance strategies to decrease net losses due to breakdown and to improve operational efficiency in this ever-evolving competitive world (Arslankaya & Atay, 2015). Total productive maintenance (TPM) is a structured approach to ensure that production is never affected by the need for maintenance. TPM ensures this by utilizing proactive and preventive maintenance techniques (Osti, 2020).

According to literature, predictive maintenance technologies which utilize industrial IoT, such as Conditions Based Maintenance (CBM) can increase the net productivity by 25% and reduce the downtime by as much as 75%(Gr et al., n.d.). CBM utilizes various sensors and algorithms to monitor the real-time running health condition of the equipment and later compares it with historical data using saved on the cloud to predict the upcoming repair before it occurs. Right after the prediction, the required parts are automatically ordered by the system and a message is sent to the technical department, which classifies the exact time and location of the repair (Gr et al., n.d.). Currently, multiple tycoons of the industry such as Bosch, GE and Johnson Controls utilize IoT enabled machines to automatically predict the required maintenance rather than relying on technical/Maintenance personal due to both financial and non-financial benefits (Iot, 2014).

2.4 **Layout Planning**

Factory layout plays a vital role in the leanness of the production facility. There is a significant interrelation in-between the technologies used and facility layout (Flinchbaugh, 1998). Production plant layout planning is used to improve the arrangement of departments, equipment, material handling equipment, storage spaces, personnel and other supporting services in such a way that the distance travelled for material handling is minimized to the extent that it saves financial resources, supports sustainable production and improves space utilization (Drira et al., 2007). When planning the layout of the production facility, strategies employed for the production plant also takes a significant role in the leanness of the firm. Essentially, lean manufacturing can also be seen as a layout approach, which aims to minimize the wastages in the factory by streamlining the flow of raw materials and subassemblies, reducing the distance travelled by the workers, reduces Takt time and minimizes congestion. This ultimately not only improves warehousing and inventory but also improves the process flow and information flow of the organization (Karim & Arif-Uz-Zaman, 2013).

Facility layout design is not a simple, straightforward problem; it is an ill-structured problem, which takes into account multiple criteria simultaneously (Shouman et al., 2015). The majority of the literature argues that facility layout problems should be grasped as a combination of both design and optimization problems. (Heragu 1997; Yang and Kuo 2003, Shouman et al., 2015). In the current literature, a significant amount of research has been done on the quantitative issues of facility layout problems such as Cost, Material handling and emissions produced during manufacturing. Even though multiple analytical approaches might produce a good solution to the problem on paper, they might not be applicable in the real world due to non-quantifiable objectives such as safety requirements, hygiene requirements, security needs, etc. In the facility layout design of any production plant, it is essential to consider not only the quantitative data for quantifiable objectives but also, the qualitative data for the non-quantifiable objectives such as lean production (Hailemariam, 2010).

2.4.1 Discrete and continuous models

As mentioned before, the core objective of the layout planning problem is to minimize the net cost related to projected interactions in-between different machines and departments, i.e. Material flows and the cost associated with the flows. The layout of any production plant can be represented in either a discrete or a continuous manner. In discrete modelling, a grid is defined where all departments are restricted to a specified shape, and they are later placed with the predefined grid. In continuous representation, departments are not bounded by a grid. Hence, they can take any shape or form. According to literature, discrete and continuous formulations mostly lead to Quadratic Assignment Problems (QAP) or Mixed Integer Programming (MIP), which are extremely hard to solve for large number of departments.

2.4.1.1 Quadratic Assignment Problem (QAP)

The optimization of discrete models is referred to as QAP (Drira et al., 2007). In these models, the entire plant is divided into a number of rectangles that have the same shape, orientation, and areas. Each department of the production facility is assigned a specific number of blocks. In such problems, the distance between departments is taken as the distance between the centroids of the departments (Hailemariam, 2010). QAP aims to find the optimal solution by relocating departments so that the net transportation costs are minimized(Cannas et al., 2019). One of the core disadvantages of QAP is that the size of the problem increases as the size of blocks on the grid is minimized. Figure 2.11 illustrate discrete models in QAP, where numbers from 1-8 represent eight different departments and their location according to each other (Hailemariam, 2010).

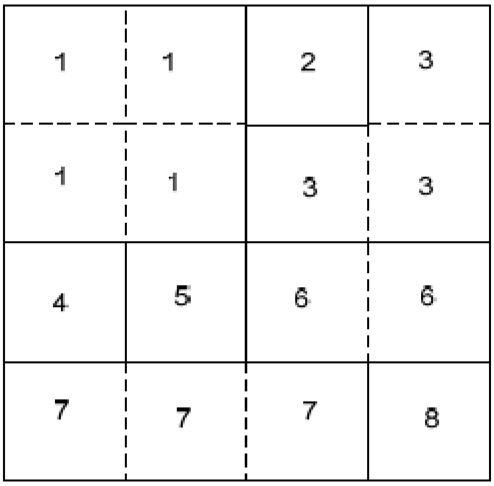


Figure 2.11. Representation of discrete models in QAP (Hailemariam, 2010)

2.4.1.2 Mixed Integer Programming (MIP)

In the current literature, the optimization of continuous models is referred as the Mixed Integer Programming model (Meller, Narayanan et al. 1998). In such models, departments' locations are addressed either by their centroids or by the position of their bottom left corner, department length, and department width. In these models, the departments must be placed on a planer site not to overlap each other. Figure 2.12 illustrates the continuous models in MIP (Hailemariam, 2010). MIP models have been studied in detail by a number of researchers (Bazaraa & Sherali, 1980; Chraibi et al., 2021; Deechongkit & Srinon, 2014; Songwut & Srinon, 2014; Yang et al., 2019). Israel et al. developed a MIP model for the production planning of footwear companies; with their model, authors decreased the net inventory, improved the quality of production, and decreased the lead time by 25% (Israel et al., 2021).

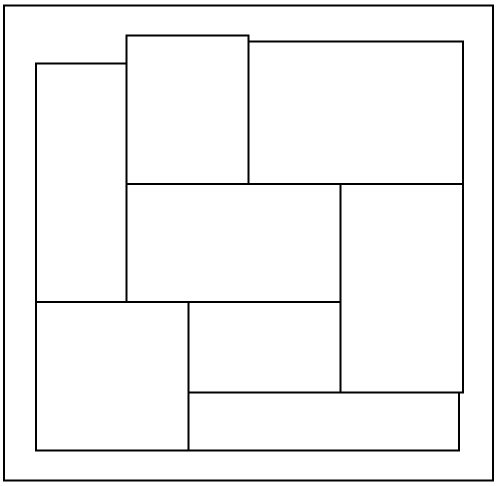


Figure 2.12. Representation of Continuous models in MLP (Hailemariam, 2010)

2.4.2 The Systematic Layout Planning

Systematic layout planning (SLP) was developed in the 1970s by Muther and is to date, one of the most well-known and well-adapted facility layout design approach (Hailemariam, 2010). One of the main reasons it has remained popular and has been the got to approach for more than 30 years is due to its systematic and straightforward step-by-step approach, which yields reliable results (Muther & Hales, 2015). SLP is mainly used for material flow and layout improvement, which are vital for lean production facilities. SLP has four main phases, as shown in Figure 2.13.

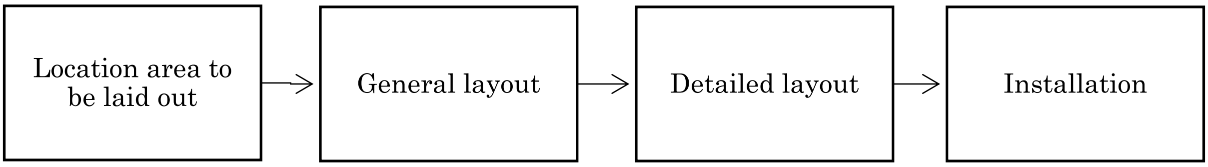


Figure 2.13. Four phases SLP

Phase 1 is determining the location of the plant. Location can play an instrumental role in the design of the layout due to resource availability and usage. In phase 2, development of general layout, firstly, an understanding of the flow of materials between the production plant facilities using flow matrix such as, To-From matrix, Machine-Machine matrix are made. The second step is the development of an understanding of adjacency requirements in between facilities of the production plant. This is done using relationship charts. The third step is of determining the space required by each department. The fourth step is of balancing the space required with space available. And the last step is of developing an understanding of the practical constraints such as budget, emissions, H&S etc. A general layout is formed at the last stage. The steps of phase 3 are precisely the same as phase 2 but it is related to the placement of machines in the department rather than the department in the facility.

Figure 2.14, shows phase 2 and phase 3 of SLP, where the PQRST approach is utilized (Bastas, 2020). In this approach, ‘P’ refers to the product: Types refers to product, ‘Q’ refers to quantity: Exact quantity of product produced, ‘R’ refers to Routing: Operation sequence of each part, ‘S’ refers to services: Support services and auxiliary services, and lastly ‘T’ refers to timing: time taken for each component to be produced.

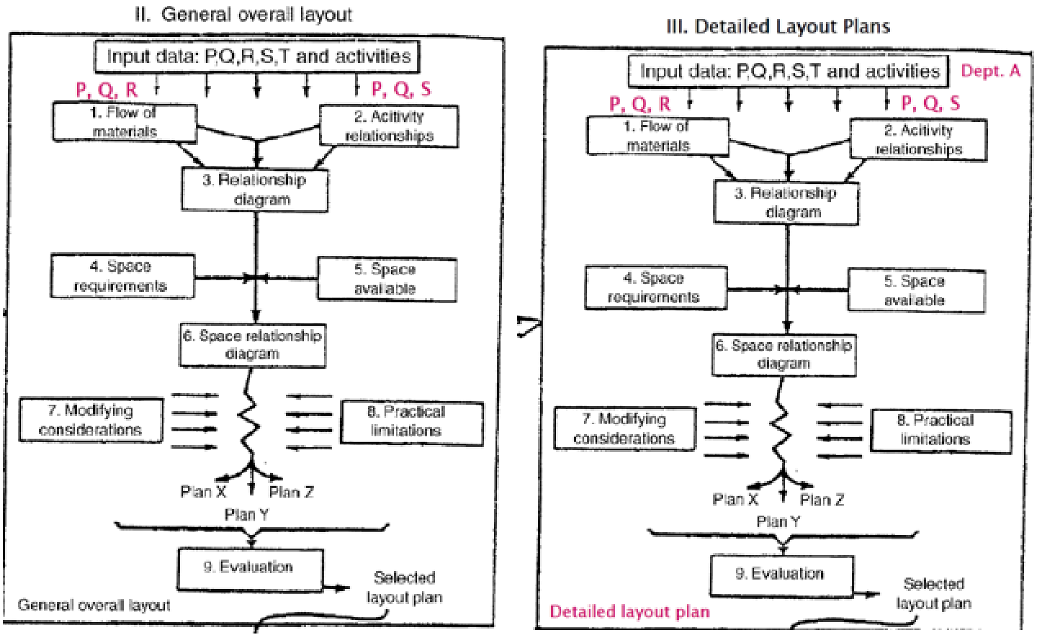


Figure 2.14. Phase 2 and phase 3 systematic layout planning detailed steps

According to litreature, SLP is one of the go-to approach for lean production plant design. Abdullah et al. stressed the importance of SLP in Job shop type layout planning. They used From-to chart to improve the distance travelled by 95% (Abdullah & Lash, 2015). Asad et al. utilized modified SLP for lean layout design of a multinational firm switchgear facility in Karachi. Using SLP, they decreased material flow and lead time by 26.4% while saving 18$ per panel (Asad et al., 2016). However, both case studies did not utilize VSM, GT, or any validation model or suggest anything related to continuous improvement or TPM, which are of key importance for the lean organization.

2.4.3 The Layout Improvement Algorithms

There are two main types of optimization approaches for facility layout problem (FLP); Exact approaches, such as branch and bound models and Approximated approaches, such as heuristics and meta-heuristics models. Both methods aim to find practical and feasible solutions; which meets the demands and needs of the decision-maker or aim to find a global or local optimum solution for one or several objectives (Drira et al., 2007). Due to the complexity of optimum approaches such as QAP and MIP, most literature focuses on heuristic approaches, i.e., heuristic algorithms or approaches like SLP. Heuristic algorithms are classified into construction and improvement algorithms. In construction algorithm approaches, the layout of the plant is made from scratch. In improvement algorithm approaches, the algorithm improves the initial current layout based on the criteria set by the designer (Hailemariam, 2010).

Construction techniques utilize either quantitative data or qualitative data such as volume of trips, Distances between departments, adjacency constraint etc., to solve the FLP from scratch without an initial layout. Computerized Relationship Layout Planning (CORELAP), BLOCPLAN, Automated Layout Design Program (ALDEP) are the most well-known construction algorithms. On the other hand, Improvement techniques require not only the data needed for the construction techniques, but also require the initial layout of the production plant. Computerized Relative Allocation of Facilities Technique (CRAFT) and Multi-Floor Facility Layout Problems (MULTIPLE) are the most well-known construction algorithms (Drira et al., 2007; Meller & Bozer, 1996; Shouman et al., 2015; Singh & Sharma, 2006).

2.4.3.1 ALDEP and CORELAP: construction algorithm

ALDEP and CORELAP are heuristic construction type algorithms that use trial and error methods to obtain a *"good enough"* solution for a given facility. These algorithms use preference ratings to calculate the Total Closeness Rating (TCR). TCR is a numerical sum of the preference ratings: relative closeness of one department to another based on Muther diagram. Departments with the highest TCR are placed first, and later others are placed later. CORELAP is based on the assumption that each department in the facility has a dispatch and receiving area closest to its nearest neighbour. CORELAP utilizes Relationship charts, the number of departments, department sizes and Muther diagrams to place the “high raking” departments in the centre of the plane. ALDEP is based on CORELAP. It uses the same input parameters as CORELAP other than the area: ALDEP uses length and the width of the department rather than the area.

Furthermore, ALDEP has a variation of randomness. ALDEP places the department with the highest TCR randomly on the plane and then sets other departments accordingly. ALDEP generates numerous layouts and leaves the final layout's evaluation and decision on the facility planer (Bick & Oron, 2011).

2.4.3.2 Graph-Theoretic Approach

The use of graph theory in FLP can be dated back to the early 1960s in BLOC layout design using relationship charts (John & Hammond, 2000). Graph theory utilizes the desirability of placing adjacent departments with each other, using closeness rating. Graph theory aims to maximize this closeness rating to reach the best possible design (Shouman et al., 2015). The graph-theoretic approach (GTA) was initially developed in 1983 by Foulds and Robinson (John & Hammond, 2000). GTA is an algorithmic approach mainly based on classical graph theory. GTA utilizes a number of concepts such as Planar graph, Maximal Planar Graph, Dual Graphs, Edges (Arcs) (Bastas, 2020). The method developed by Foulds and Robinson focused on firstly maintaining maximal planarity and not on flow minimization. John and Hammond later improved the method by Foulds and Robinson by concentrating on both maintaining maximal planarity and flow minimizations. Their methodology produced either same or better results on identical data sets (John & Hammond, 2000).

2.4.3.3 Computerized Relative Allocation of Facilities Technique (CRAFT)

CRAFT is one of the most well-known algorithm used for facility layout and planning. CRAFT uses flow data such as Flow matrix, area of departments, cost matrix and one initial design as input parameters. The input parameter *'initial layout'* can be the current layout of the production facility or the prospective layout developed by other algorithms such as GTA and SLP. The algorithm aims to minimize the net cost of material handling by pair-wise exchange of the departments in the production facility. Equation 2.1 is the cost minimization equation used in the CRAFT algorithm.

$$Min\ C = \sum_{i=1}^{n} \sum_{j=i+1}^{n} f_{ij}\ c_{ij}\ d_{ij} \qquad (2.1)$$

Where,

C: Net cost

f_{ij} : Frequency of trips / flow rate

c_{ij} : Cost of transfer from i to j

d_{ij} : Centroid distance from i to j

Distance between departments is calculated using the centroid of the departments. CRAFT considers each department to occupy multiple cells, according to the scale set by the plant developer. The type of distance used in the calculation can be either Rectilinear or Euclidian.

If the type of distance used for calculations is Euclidean, Equation 2.2 is used to calculate d_{ij}.

$$d_{ij} = |\Delta x| + |\Delta y| \qquad (2.2)$$

If the type distance used for calculations is Rectilinear, Equation 2.3 is used to calculate d_{ij}

$$d_{ij} = \sqrt{(\Delta x)^2 + (\Delta y)^2} \tag{2.3}$$

Equations 2.4 and 2.5 are used to calculate the total distance between the centroids of the two departments.

$$\Delta X = \frac{1}{A} \int_{y_1}^{y_2} \int_{x1}^{x2} xdxdy = \frac{1}{2A} (x_2^2 - x_2^2) * (y_2 - y_1) \tag{2.4}$$

$$\Delta Y = \frac{1}{A} \int_{x_1}^{x_2} \int_{y1}^{y2} ydxdy = \frac{1}{2A} (y_2^2 - y_2^2) * (x_2 - y_1) \tag{2.5}$$

CRAFT calculates the Rectilinear or Euclidean distances between all department centroid and stores the values in the distance matrix. Later it contemplates, all feasible two-way of three-way departments exchanges, which could lead to the maximum reduction in the net costs. Once the best possible exchange with maximum cost reduction is identified, CRAFT updates the facility's layout. It then recalculates the centroids of each department, forms the distance matrix, and calculates the new net cost to complete the first iteration. CRAFT then repeats possible two-way or three-way departments' exchanges and carries out the iterations until exchanges do not result in decreased net costs 'C'. (Tompkins, James John A. et al., 2011).

Even though CRAFT yields reasonable results, there are still some issues that need to be dealt with. CRAFT can only carry out pairwise exchanges if the departments are adjacent or of equal size. Non-adjacent departments with different sizes cannot be exchanged by CRAFT (Tompkins, James John A. et al., 2011). Secondly, all in all, CRAFT has only one objective function; reduction of costs. In the current era, several others factors such as health and safety, emissions, lead time etc., also play a significant role in facility layout and planning; hence they should be considered.

2.5 Assessment models and tools

Before developing the layout of any production plant, it is essential to evaluate and examine current operations and activities to improve the leanness of the production plant (Lyons et al., 2013). In the current literature, both researchers and practitioners have developed several mechanisms and methodologies to evaluate the effectiveness of lean production plants. Current lean tools, such as, Kanban, JIT, TPM etc., focus on *'how to make an organization leaner'* instead of assessing how measuring *'how lean an organization is'.* According Wan et al. (?), VSM is one of the most viable methods to assess the production plant's leanness. VSM methodology developed by Rother and Shook is one of the most frequently used lean assessment tools (Brito et al., 2020). Bayon and Korvin developed a fuzzy logic-based lean assessment tool that compared the organizations with the Honda Motor Company as a lean benchmarking firm. They used JIT, Kaizen and quality control as the core lean indicators (Bayou & de Korvin, 2008). Numerous lean assessment surveys have been developed by researchers and practitioners to escort organization towards lean manufacturing (James A. et al., 2001; Laoha & Sukto, 2015; Wickramasinghe, 2017). The scores of the indicators in the surveys can be compared with the ideal conditions set beforehand, to assess the current state of the organization and the improvement that can be planned (Wan & Frank Chen, 2008). The lean enterprise self-assessment tool (LESAT) developed at the Massachusetts Institute of Technology is one of the most recognized lean assessment tool. It uses surveys to compare the current leanness to the desired leanness of the production plant (Brito et al., 2020). However, LESAT requires responses from significantly large number of people (*LAI ENTERPRISE SELF-ASSESSMENT TOOL (LESAT)*, 2012). Association for Manufacturing Excellence (AME) developed a benchmarking tool name *'AME lean sensi ®'* to assess the current leanness of the production plant. This tool benchmarks the organization against the esteemed AME Excellence award recipients. AME Lean Sensi is one of the go-to approach to aid the organizations in identifying the potential areas of improvement (*Lean Sensei | Association for Manufacturing Excellence*, n.d.).

CHAPTER 3

CURRENT STATE AND EMPIRICAL DATA

The chapter aims to introduce and identify the current state of the manufacturing plant, i.e. current production methodology, machines utilized, and the production plant's overall flow. The case study was used to evaluate and test the LSLP step by step approach developed in chapter 4.

3.1 The case study: Company – Company X

Company X is a purified bottled water production company located in Nicosia, Turkish Republic of Northern Cyprus (TRNC). The company was founded in 2001 in Güzelyurt Mevlevi, by Giro group of companies. Company X received European Standards certificates ISO 9001-2000, ISO 22000 and the World Food Hygiene Certificate in 2007. In 2008, company opened its state-of-the-art laboratory in cooperation with United Nations Development Programme (UNDP). Currently Company X is one of the largest purified water supplier in TRNC with a daily production capacity of 500,000 litres. Company X has seven main products, which are categorized into four different types. Table 3.1 list the products and their types.

Table 3.1. Company X products

Product No.	Name	Bottle Type
1	250ml water bottles	Type-1

2	0.3 litre water bottles	Type-2
3	0.5 litre water bottles	
4	1.5 litre water bottles	
5	5 litre water bottles	Type-3
6	10 litre water bottles	
7	19 litre water bottles	Type 4

Company X currently has a 1500 square meter factory located in Nicosia Industrial Zone. The factory has four main production lines, each manufacturing a different set of products, as shown in Table 3.2.

Table 3.2. Company X Production lines

Production line No.	**Name**
1	250ml water bottles
2	0.3 litre water bottles
	0.5 litre water bottles
	1.5 litre water bottles
3	5 litre water bottles
	10 litre water bottles
4	19 litre water bottles

3.2 Bottled water process flow at Company X

3.2.1 Type-2 and Type-3 products

All the Type-2 and Type-3 Polyethylene terephthalate (PET) bottles are manufactured locally at the production plant using extrusion blow moulding. In the extrusion blow moulding machine, preforms are first heated at specific temperatures and later clamped inside the mould. Air at 40 bars is blown in to the preform, which pushes the plastic inside to take the shape of the mould. Company X imports preform, caps and stickers every three months from external suppliers. After the blow moulding process, empty PET bottles are manually transported to the assembly line.

In the assembly line, empty bottles are washed with fresh filtered ozone water to minimize any external contamination. Later PET bottles are taken to the filling station and then to the capping station via conveyers, where water bottles are filled and capped accordingly. PET bottles are conveyed to the labelling machine and dating station where they are labelled with the brand of the company or the customers' brand, using PVC shrink labelling machine. Next, they are dated with the best before date and the batch number. While on the conveyor system, water bottles are constantly checked for deformation or impurities to maintain quality control. Lastly, these bottles are conveyed to the packaging station. The packaging station sorts the bottle in the correct order, and shrink wraps them in packs of 2, 6, or 24, according to their sizes. Figure 3.1 summarizes the general process for Type-2 and Type-3 products.

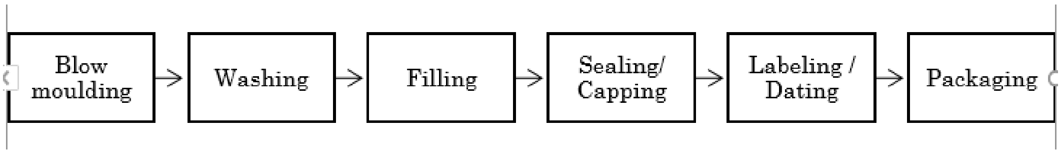


Figure 3.1. Purified water bottled production processes for Type 2 and Type 3 products

3.2.2 Type-4 water bottles

Type-4 Polyethylene terephthalate empty bottles are retrieved from customers or bought from the supplier on need basis. These bottles are first taken to the inspection station, where they are inspected for damages and external contamination. If the bottles are damaged physically, they are discarded. In case algae is present in the bottles, they are shipped to the chemical wash station, cleaned manually using chemicals. After the initial inspection and chemical wash, they are put on a conveyer which transports them to Type-4 production line.

In the second stage, empty bottles are labelled and then shipped to the assembly line. They are washed and cleaned with fresh filtered ozone water for hygiene reasons in the assembly line. Later, Type-4 bottles are taken to the filling station where they are filled and lastly to the capping station. Figure 3.2 summarizes the general process Type-4 product.

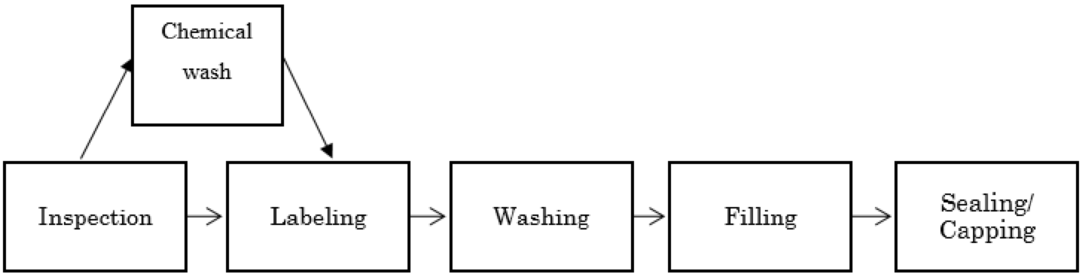


Figure 3.2. Purified water bottled production processes for Type-4

3.2.3 Type-1 products

Type-1 250ml cups are made on a single *'Automatic plastic cup water filling machine'*. This machine automatically manufactures the cups, washes them and finally seals them automatically. After the production of cups Type-1 products are packed in cartons and then shipped to pallet shrink wrapping station.

3.3 Description of Machines

The company currently has four assembly lines, nine main machines and three support machines other than MHDs. Machinery present at Company X are pneumatically operated or by electricity or by a combination of both. All the machinery and equipment used by Company X are imported from Turkey. Table 3.3 summarizes the list of primary machines, assembly lines, power source, type of machines and operations performed by the machines.

Table 3.3. List of machines at Company X

M/C no.	**Name**	**Operation**	**Power source**	**Type**
1	Type-2 blow moulding machine	Blow moulding	Pneumatic and Electric	Main
2	5 litre blow moulding machine	Blow moulding	Pneumatic and Electric	Main
3	10 litre blow moulding machines	Blow moulding	Pneumatic and Electric	Main
4	Rotary sorter	Sorting	Electric	Main
5	Type-2 litre assembly line	Bottle washing	Pneumatic and Electric	Assembly

		Filling	Pneumatic and Electric	
		Capping	Pneumatic and Electric	
6	Type-3 litre assembly line	Bottle washing	Pneumatic and Electric	Assembly
		Filling	Pneumatic and Electric	
		Capping	Pneumatic and Electric	
7	Type-4 assembly line	Bottle washing	Pneumatic and Electric	Assembly
		Filling	Pneumatic and Electric	
		Labelling	Electric	
8	Type-2 litre labelling and dating machine	Dating	Electric	Main
		Labelling	Electric	
9	Type-3 litre labelling and dating machines	Dating	Electric	Main
		Labelling	Electric	
10	Type-1 assembly	Filling	Pneumatic	Assembly
		Sealing	Electric	
		Packaging	Pneumatic and Electric	
		Making		

			Pneumatic and Electric	
11	Type-2 litre packaging machine	Packaging	Electric	Main
12	Type-4 litre packaging machines	Packaging	Electric	Main
13	Pallets shrink wrapping station	Shrink wrapping	Electric	Main
14	Main air compressor	Produce 40 bar pressure	Electric	Auxiliary
15	4 spare compressors	Cover up for machine M	Electric	Auxiliary
16	Water purification equipment	Purify water	Pneumatic and Electric	Auxiliary

Air Compressor is one of the most vital machines present at the production plant since almost all machines utilized at the production plant are pneumatically operated at a pressure of 40 bars. Air compressors are used to fill the air reservoir, which in turn maintains the air pressure. Company X currently has one central compressor and four small secondary compressors if the first one develops a fault.

3.4 Current Plant Design

The current production facility of Company X is located in Nicosia Industrial Zone. The production facility is made single standalone shed covering around 1500sq/m. Production facilities can be categorized into 25 main departments. Table 3.4

tabulates the 25 departments and the machines present in each department. The route followed by seven different products were determined and are listed in Table 3.5.

Table 3.4. Department names and machines in each department.

Department number	**Department name**	**Machine**
D 1	**A**	Type-2 blow moulding machine
D 2	**B**	5 litre blow moulding machines
D 3	**C**	10 litre blow moulding machines
D 4	**D**	Type-2 litre cleaning, filling and capping machines
D 5	**E**	Type-3 Washing, filling and capping machines
D 6	**F**	Type-4 cleaning, filling and capping machines
D 7	**G**	Type-2 labelling machine and dating machine
D 8	**H**	Type-3 labelling machines
D 9	**I**	Type-1 assembly machine
D 10	**J**	Type-2 packaging machine
D 11	**K**	Type-3 litre packaging machines
D 12	**L**	Shrink wrapping station
D 13	**M**	Storage A (preforms/caps/labelling material/PET sheets)
D 14	**N**	Storage B
D 15	**O**	Storage C
D 16	**P**	Rotary sorter
D 17	**Q**	Type-2 Washing Station
D 18	**R**	Main air compressor and air storage tank
D 19	**S**	Secondary air compressors
D 20	**T**	Air boosters
D 21	**U**	Laboratory
D 22	**V**	Manager office
D 23	**W**	Filtration plant
D 24	**X**	Tool Room
D 25	**Y**	Water storage tank

Table 3.5. Department Route followed by each product

Part No.	Name	Department route
1	250ml water bottles	M>I>L>N>O
2	0.3 litre water bottles	M>A>P>D>G>J>L>O
3	0.5 litre water bottles	M>A>P>D>G>J>L>O
4	1.5 litre water bottles	M>A>D>G>J>L>O
5	5 litre water bottles	M>B>E>H>L>O
6	10 litre water bottles	M>C>E>H>L>O
7	19 litre water bottles	O>N>Q>F>O

To further analyse the departments, 1:1 3-D models were made in factory design utilities on AutoCAD mechanical and Autodesk inventor 2020 environment. Figure 3.3 shows the 2D model of the current production facility. Departments A to Y are marked on the figure. Figures 3.4 and 3.5 illustrate the 3D Model of the existing facility.

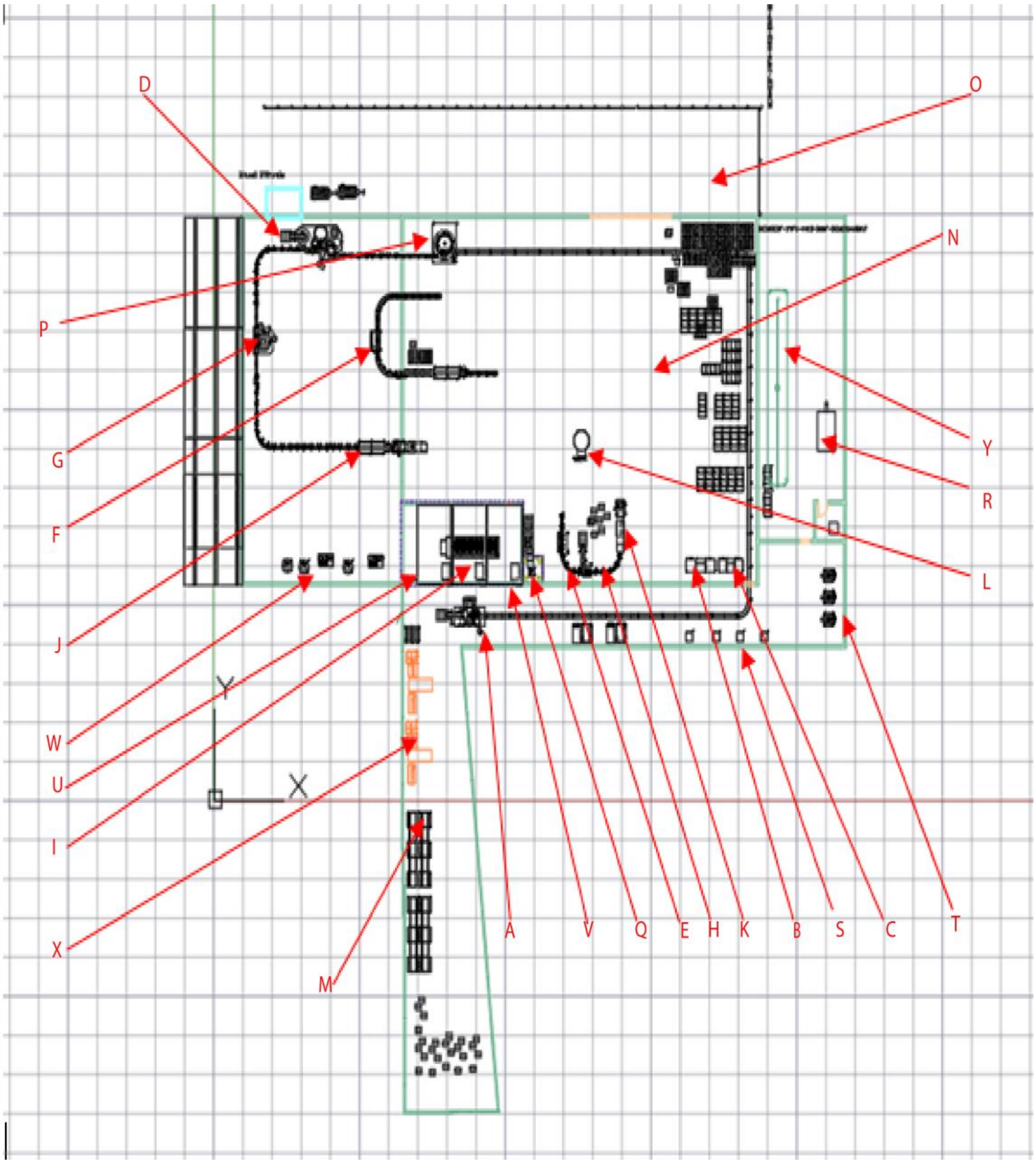


Figure 3.3. AutoCAD mechanical 2D model of Company X

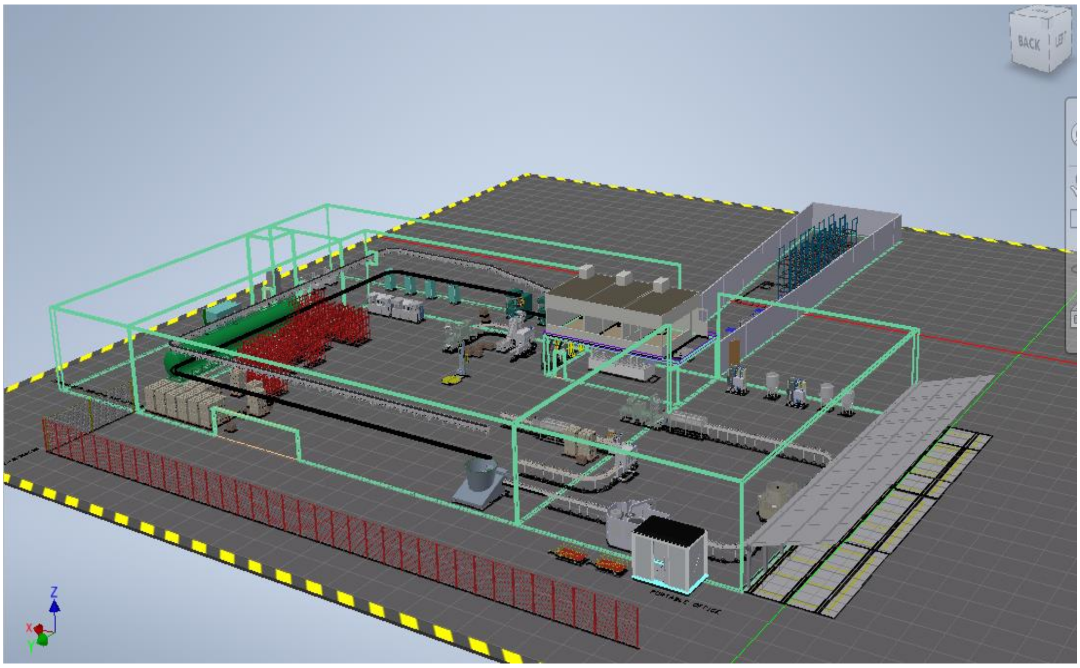


Figure 3.4. Autodesk Inventor 3d model of Company X (Front right)

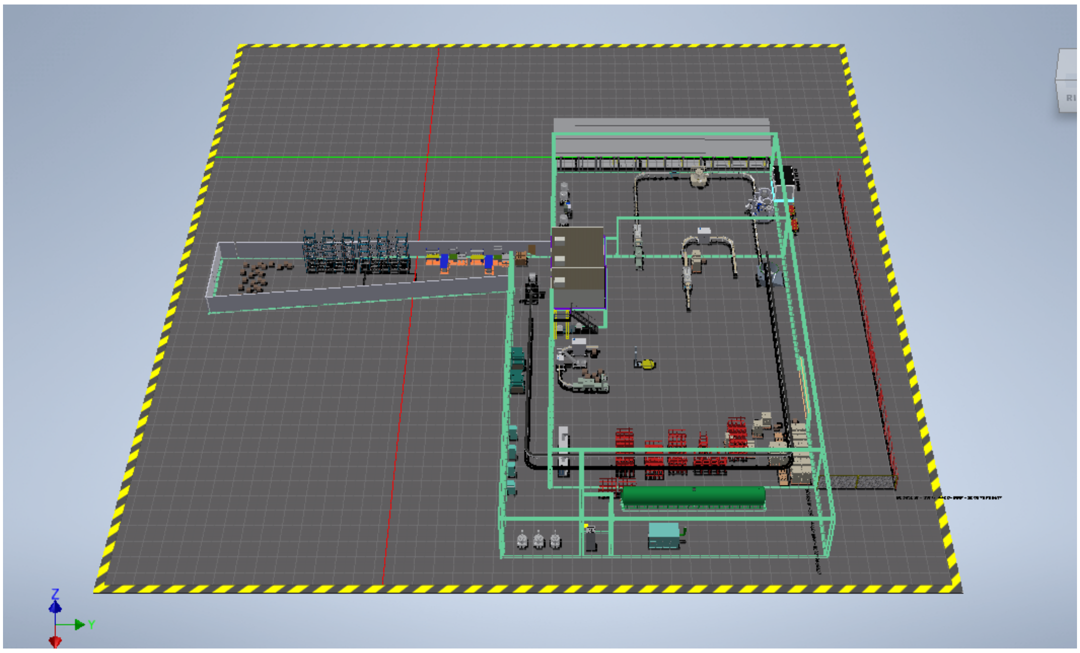


Figure 3.5. Autodesk Inventor 3d model of Company X (Back)

3.5 **Fixed departments restrictions**

Even though there are 25 departments, after initial analysis and discussions with factory owner and engineer, it was evident only location of 16 departments can be changed to minimise the total distance travelled by the products. Table 3.6 tabulates the department number, department name and machine names of the fixed departments.

Table 3.6. Fixed Departments of Company X

Department number	Department name	Machines
D 1	**A**	Type-2 litre blow moulding machine
D 13	**M**	Storage A (preforms/caps/labelling material/PET sheets)
D 18	**R**	Main air compressor and air storage tank
D 19	**S**	Secondary air compressors
D 20	**T**	Air boosters
D 21	**U**	Laboratory
D 22	**V**	Manager office
D 23	**W**	Filtration plant
D 25	**Y**	Water storage tank

D 1 (Type-2 blow moulding machine) produce significant heat and sound; due to health and safety reasons, it is not recommended to move from the current location.

D 18 (Main air compressor and air storage tank) requires an open space located at the very end of the production plant. The current location is the only feasible location for D18.

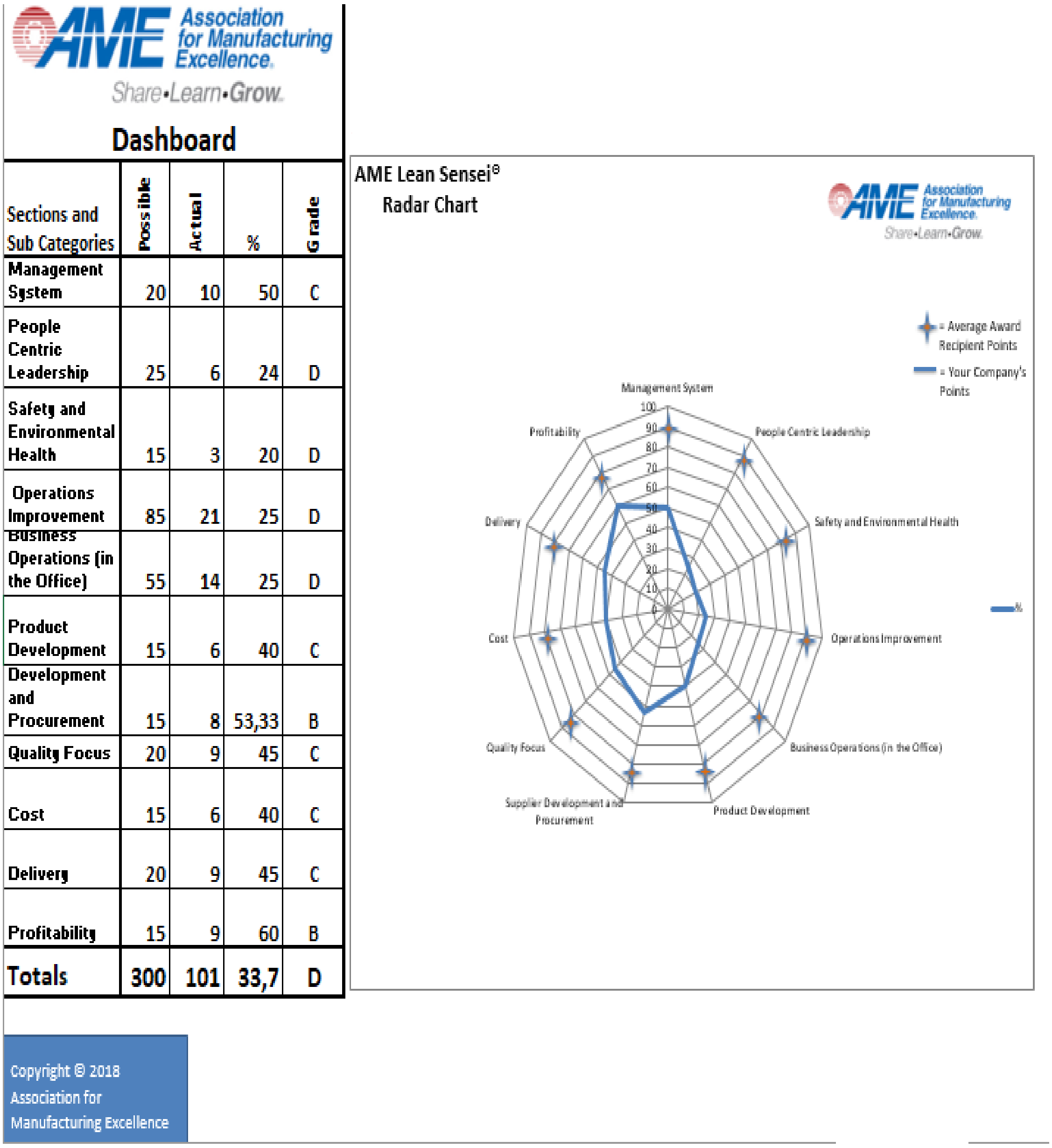
D 19 (Secondary air compressors) and D 20 (Air boosters) have no flow of products. They should be placed as close to D 18, since changing the location will decrease the efficiency of the stored air and increase the company's financial expense. Remapping the storage tank, pipes and electronics for all machines will be not economically feasible.

D 21 (laboratory) are D 22 (Manager Office) are located on the only two rooms of the 2nd floor of the production plant. They have a full view of the facility at all times. These departments should have a view of the facility at all times for administrative reasons. Therefore, shifting these two departments will require construction of new floor at other location which will not be cost effective. D 23 (Filtration plant) should be in close vicinity of the D 21 (laboratory) and away from any other type of production machines for hygiene reasons. Due to this, it is bounded to the current location. Furthermore, shifting of filtration will be financially not feasible due to the water piping system.

Shifting of D 25 (Water storage tank) will require building of an entirely new water collection and delivery system, which is not financially feasible.

3.6 Lean assessment

To assess the current manufacturing practices of Company X using Association for Manufacturing Excellence (AME) tool *'AME lean sensei ®'*, multiple visits to the production facility, GEMBA walks along with numerous interviews with CEO, site engineer, operations lead and floor workers were conducted. Figure 3.6 illustrates the radar chart of the results obtained using the tool box.



AME Association for Manufacturing Excellence

Share•Learn•Grow.

Dashboard

Sections and Sub Categories	Possible	Actual	%	Grade
Management System	20	10	50	C
People Centric Leadership	25	6	24	D
Safety and Environmental Health	15	3	20	D
Operations Improvement	85	21	25	D
Business Operations (in the Office)	55	14	25	D
Product Development	15	6	40	C
Development and Procurement	15	8	53,33	B
Quality Focus	20	9	45	C
Cost	15	6	40	C
Delivery	20	9	45	C
Profitability	15	9	60	B
Totals	**300**	**101**	**33,7**	**D**

Figure 3.6. AME lean sensei results

Company X scored less than 50% grade in 9 out 11 grading criteria. Company X scored letter grade *‘D’* in *‘Business Operation’*, *‘Operations Improvement’* and *‘Safety and Environmental Health’*. Solving these three issues will not only improve these three criteria’s but will indirectly improve other practices as well. These three criteria will be the core focus of this thesis.

Issues in *'Business operations'* are listed bellow

- Even though top management is aware about the wastes and are trying to minimize overproduction, over processing, waiting times, excess motions and defects, however, lower management is unaware of them.
- Errors and defects in production are catered to once they occur. There is little to no consideration given to the source of the errors and defects.
- There are no set inventory locations for raw materials, Kanban, work in progress and even finished goods. Inventory is placed randomly where ever they seem fit at the given time.
- Due to the current layout, material handling is not up to the mark. Company X is still following a push-based system that increases the use of resources.
- Due to the layout issues, lack of work standardization and corrective maintenance, there are frequent interruptions in manufacturing.
- Frequent MHD congestion due to ill-structured layout.
- Single entrance and exit used for Type-4 products.
- The company is unaware of the importance of VSM and has not used VSM so far.
- Even though structure is present for Type-2 production to be fully automated, there is a significant speed mismatch between different machines on the same product lines.
- Employees are not trained on the basic principles of 5s and there are no visual indicators at the manufacturing plant.
- Floor men do not get the chance to share their knowledge and expertise.

Issues in *'Operations improvement'* are listed bellow

- There is a lack of information flow and synchronization at the manufacturing facility. Line workers are unaware of the daily number of orders to be full filled.

- There is no limit on the maximum capacities that the plants can produce.
- There is no predefined work schedules. Work schedules are altered and adjusted to encounter the last-minute rushes.
- Workers do not have training or retraining period to improve the standard of the work practices.
- No visual boards to track the performance of the work.
- Only a few employees are cross-trained to work in different departments.
- Evidence of silo thinking in employees.

Issues in *'Safety and Environmental Health'* are listed bellow

- Little to no consideration is given to lowering the carbon footprint.
- Fossil fuel-generated electricity from the grid and Diesel generators are used as a backup.
- The use of electricity and other natural resource is increasing every year.
- Floor men lack the knowledge of Environmental Health and Safety (EHS).
- Evidence of poor ergonomics and safety problems during Gemba walks.
- Near misses are not recorded for future improvement.
- Inadequate use of safety gear.
- Inadequate Airflow, specifically during summers.

3.7 Issues at hand

This section briefly summarizes the list of issues of the current production facility

Layout issues

- Poor space utilization.
- Congestion due to material flow.

- Single entry and exit for Type-4 bottles.

Machinery Issues

- Speed mismatch between Type-2 bottles blow muddling machine and assembly line.
- No manual for operating machines.
- Type-2 pneumatic conveyor is non-functional; hence, work is done manually.

Maintenance

- No defined maintenance schedule.
- No training given to the technicians.

5s and visual controls

- No utilization of 5s or visual controls.

Operations

- Floor workers are not aware of the current manufacturing targets.
- Floor workers are not encouraged to share their opinion and suggestions for continuous improvement.

Health and safety

- Floor workers are not fully aware of health and safety rules.
- Lack of ventilation.

CHAPTER 4

LEAN SYSTEMATIC LAYOUT PLANNING APPROACH

The classical SLP is an easy to use, systematic step by step approach which yields reliable results. However, there are particular limitations when looking into designing of a lean manufacturing plant. The classical SLP approach developed by Muther neither includes any lean terminologies nor includes any layout algorithms that could yield superior and sustainable results. Thus, a Lean Systematic Layout Planning (LSLP) approach, which is based on the classical SLP approach and the 'Principles of Lean' approach developed by James P. Womack and Daniel T. Jones, is proposed here. In LSLP, classical four-step SLP was modified by incorporating *'lean assessment'* in-between phase 1 and phase 2 and adding *'lean initiative'* phase in-between phase 3 and phase 4, making it a systematic six-step process. Furthermore, construction algorithm Graph Theoretic Approach (GTA) and improvement algorithms (CRAFT) will be used to make different forming multiple detailed layout stage of LSLP. Figure 4.1 shows the six-step LSLP framework utilized in designing the new production plant for Company X.

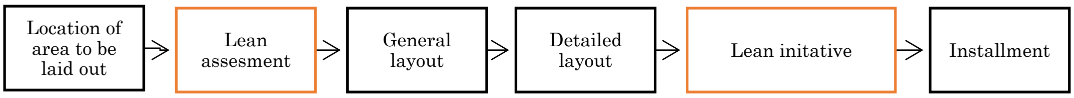


Figure 4.1. Six stages of LSLP

Stage 1: *'Location of area to be laid out'* is same as the classical SLP approach and is discussed in detail in chapter 2.

Stage 2: '*Lean assessment'* of LSLP framework aims to assess and develop an understanding of the current workings of the current production facility. Lean assessment is a 3-stage process, starting with operation analysis. The core purpose of operation analysis is to get familiar with the operational policies followed by the employees and collect data using observations, GEMBA walks, and most importantly, multiple interviews starting with the top management to the technicians and floor men. Data gathered at this stage is used to audit and benchmark the current production facility with well-established lean firms. Benchmarking and audits are essential to highlight the hotspots which could improve the leanness of the production plant. The data collected at the observation stage is used in the development of C-VSM and F-VSM. Rother & Shook recommended a four step process which is used to make C-VSM and F-VSM of the production facility. Figure 4.2 summarizes the 3rd *'lean assessment'* phase of LSLP.

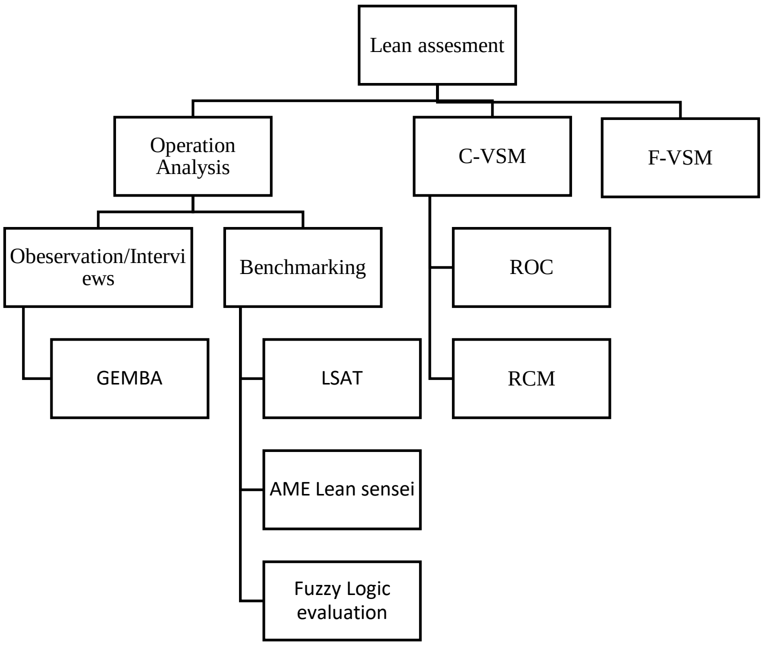


Figure 4.2. *‘Lean assessment’* stage of LSLP

Stage 3: *‘General layout’* is a three-step process, starting with flow analysis. Flow analysis is described as; Activity relationship charts and flow matrix such as part-machine matrix, machine-machine matrix and department-department matrix, To-From matrix is used to develop an understanding of the current facility. The second step is space analysis which is the same as classical SLP. The last step is drawing spaghetti diagrams. Spaghetti diagrams are made to track the movement of people, machines and paperwork at the production facility, which in turn aids in identifying issues such as congestions and non-value-added flows that should be taken care of. Figure 4.3 summarizes the 3rd *‘General layout’* phase of LSLP.

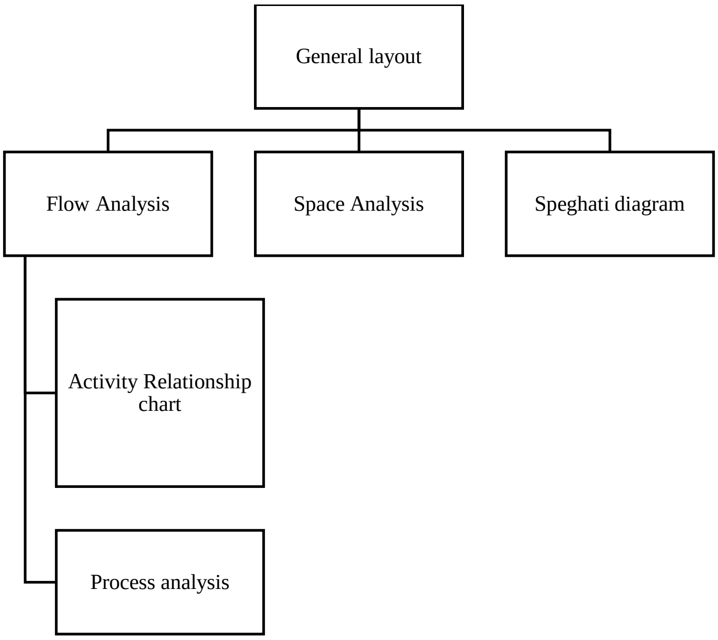


Figure 4.3. *‘General layout’* stage of LSLP

Stage 4: *‘Detailed layout’* is the most crucial stage of LSLP approach. All the data gathered in previous stages is used to model a lean sustainable layout that meets the requirements set by the plant management. In this study, Modified-CRAFT and LSLP-GTA based approaches are used to design and modify the detailed layout. Chapter 4 focuses on the LSLP-GTA based heuristic approach whereas, Chapter 5 focuses on the Modified-CRAFT approach. 2nd step in the *‘Detailed layout’* phase is model assessment. The last step of detailed layout is 2D and 3D modelling using computer-aided design applications such as Autodesk Inventor factory design utilities and walk-through simulation using Autodesk Navisworks. 3D modelling and simulations aid in visualizing the new layout; it shows space constraints that might be missed in simple 2D models. Figure 4.4 summarizes the 4th *‘Detailed layout’* stage of LSLP.

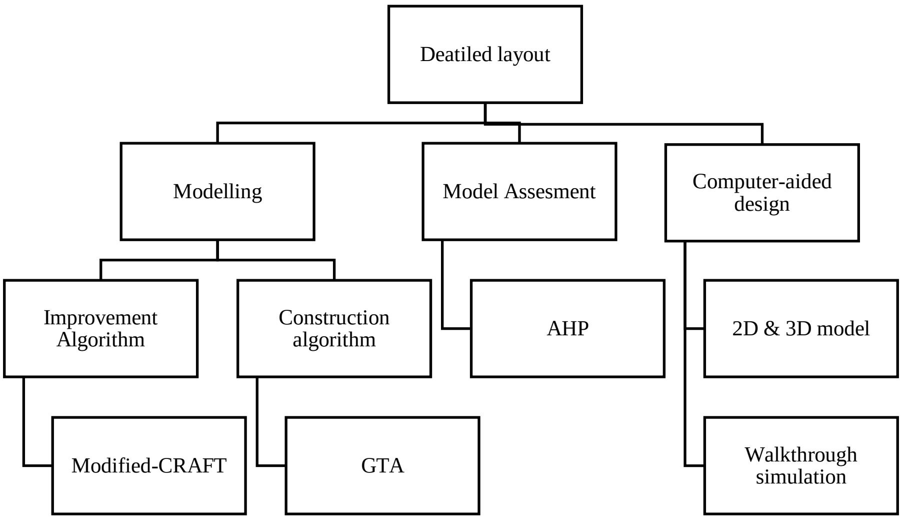


Figure 4.4. *'Detailed layout'* phase of LSLP.

Stage 5: *'Lean initiative'* of LSLP framework core purpose is to develop the lean culture in the organization. In stage 5, core lean policies and strategies are evaluated and plans are made for implementation of TPM, Health & Safety, Kanban, Kaizen, 5s and Visual plans. Figure 4.5 summarizes the 5th *'Lean initiative'* stage of LSLP.

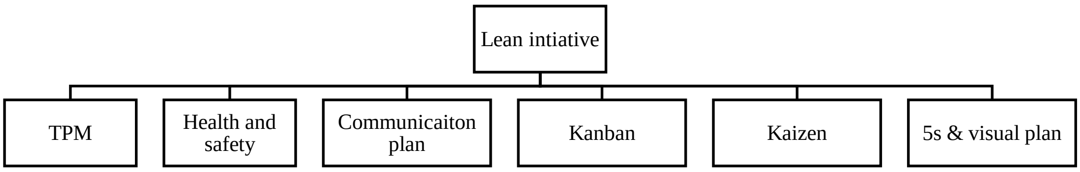


Figure 4.5. *'Lean initiative'* stage of LSLP

Stage 6: *'Implementation'* is the last and the final stage of LSLP. In this stage, all the data gathered at previous stages are catalogued and presented to stakeholders for final approval before implementation. Figure 4.6 illustrates the complete model of the LSLP core model.

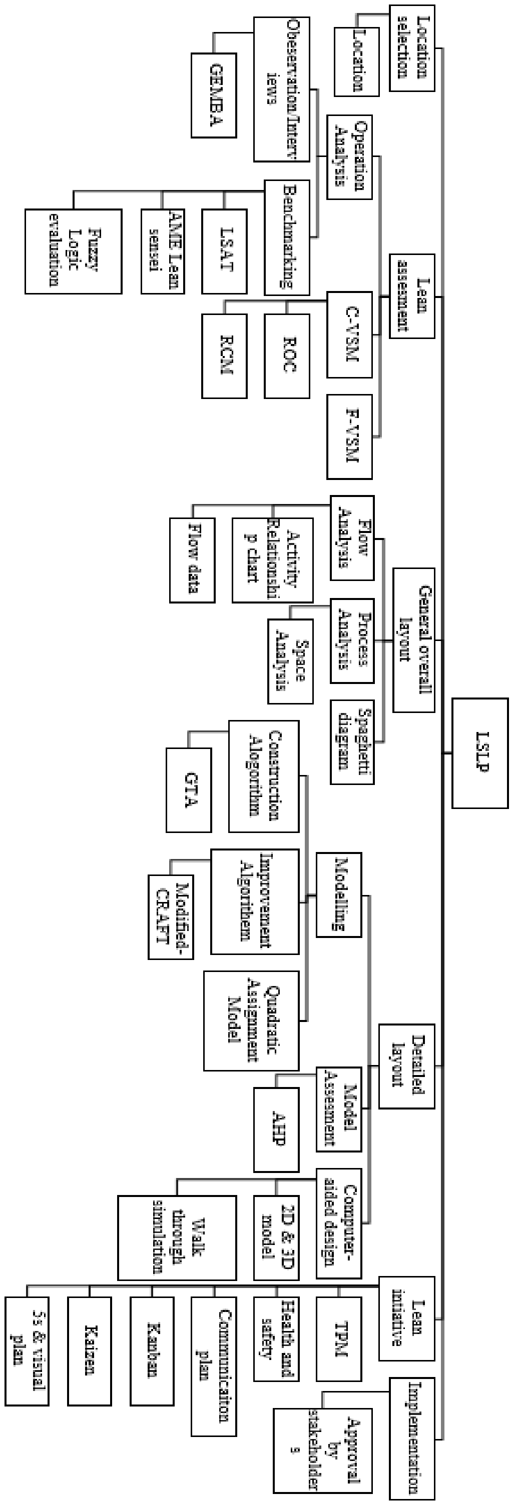


Figure 4.6. LSLP core model

4.1 Layout and production type

After an in-depth analysis of the products produced and the Company X's production facility layout, layout type and production type for the new facility were determined. Batch production with a cellular layout was selected for the new production facility due the following reasons listed below.

- A single blow moulding machine and the assembly line is used for manufacturing and filling of Type-2 bottles. The same production line can easily fulfil the current orders in batches.
- Type-2 bottles production can be fully automated once blow moulding and air conveyor is functional. This will not only improve the lead time but also decrease the quality issues
- Single production line is used for filling Type-3 bottles. Production volume is low; hence, buying new machinery will incur extra costs and is not required. Batch processing can effortlessly fulfil the current and the predicted demands of the factory.
- Cellular type layout is chosen solely because the current factory has 4 separate assembly lines that can easily be isolated since only one machine is shared between the assembly lines.
- Factory manager and Lead engineer showed interest in cellular type approach during GEMBA walks and interviews.

4.2 LSLP Stage 1: Location selection

As mentioned in the previous chapter, the location of the production facility of Company X is predefined by the stakeholders; hence location analysis was not required.

4.3 LSLP Stage 2: Lean assessment

Operation analysis of LSLP was done for Company X and is discussed in chapter 3. Value Stream Map is one of the most important tools in assessing any lean production facility since it evaluates and gives the snapshot of the entire facility in one single sheet of paper. Framework developed by Rother and Shook was used to conduct value stream analysis. The first step is of identifying product families using product family matrix. In this study, Rank-order clustering (ROC) approach was used for identifying product families. It used part-machine process indicator matrix shown in Table 4.1.

Table 4.1. Part-machine process indicator matrix

		Machine											
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
	1	0	0	0	0	0	0	0	0	**1**	0	0	0
part	**2**	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**
	3	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**
	4	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**
	5	0	**1**	0	0	**1**	0	0	**1**	0	0	**1**	**1**
	6	0	0	**1**	0	**1**	0	0	**1**	0	0	**1**	**1**
	7	0	0	0	0	0	**1**	0	0	0	0	0	0

4.3.1 Rank-Order clustering

ROC is a cluster analysis approach used for group technology. In ROC part-machine process indicator matrix is used to form machine and product clusters. Firstly, binary weights are assigned to each column of the part-machine process indicator matrix using Equation 4.1.

$$BW_j = 2^{m-j} \tag{4.1}$$

Where BW_j is the column's binary weight, m is the number of machines and j number of the column number of part-machine matrix. Secondly, the binary value of each row *'i'* was converted to the decimal equivalent of each row using Equation 4.2. Next, rows are rearranged in descending order of decimal equivalent value.

$$DE_i = \sum_{j=1}^{m} 2^{m-j} \, a_{ij} \tag{4.2}$$

Where, DE_i is the decimal equivalent. Later, binary weights were assigned to each row of the part-machine matrix using Equation 4.3.

$$BW_i = 2^{n-1} \tag{4.3}$$

Where BW_i is the binary weight of the row and *'n'* is the number of products in part-machine indicator matrix. Next, binary value BW_i of each column *'j'* was converted in to decimal DE_j equivalent of each column, using Equation 4.4. Finally, columns are rearranged in descending order of decimal equivalent value.

$$DE_j = \sum_{i=1}^{n} 2^{n-1} \, a_{ij} \tag{4.4}$$

The process mentioned above are repeated until no shifts of rows or columns are possible in part-machine indicator matrix. Table 4.2 given below shows the final clustering using ROC. Complete iterations can be seen in Appendix A.

Table 4.2. Rank order clustering final matrix

			M	**A**	**C**	**H**	**I**	**N**	**E**				
		L	**D**	**A**	**G**	**J**	**E**	**H**	**K**	**B**	**C**	**F**	**I**
	2	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	0	0
P	**3**	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	0	0
A	**4**	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	0	0
R	**5**	**1**	0	0	0	0	**1**	**1**	**1**	**1**	0	0	0
T	**6**	**1**	0	0	0	0	**1**	**1**	**1**	0	**1**	0	0
	7	0	0	0	0	0	0	0	0	0	0	**1**	0
	1	0	0	0	0	0	0	0	0	0	0	0	**1**

It can be seen from the final ROC matrix there are a total of 4-part families and four machine families. Machine L is low cost and small in size; it can be bought for a separate production line if needed. Table 4.3 summarizes the results of ROC.

Table 4.3. Rank order clustering final results

Name	Part family	Machine family
Type-1	1	I
Type-2	2,3,4	D, A, G, J, L_1
Type-3	5,6	E, H, K, B, C,L_2
Type-4	7	F

4.3.2 Value Stream Mapping

Even though four product families were identified with Rank Order Clustering (ROC), in the current value stream map (C-VSM) there is a separate additional value stream map for 0.3lt and 0.5lt bottles. This is done because currently the factory uses a rotary sorter to arrange the small bottles in order since the air conveyor isn’t working. Air conveyors can automatically sort and orient the bottles in the correct order for the production line. The given VSM will give us the full view of the production facility and minimize the risk of missing critical information about the material flow.

The current state value stream map was first made manually on a single page and then converted to digital form in Adobe Illustrator CS7. This map contains all the typically used symbols from literature. The developed C-VSM includes valuable information such as the time taken, inventory levels, number of operators, cycle time, available time and lead time. One of the drawbacks of a Value Stream Map is that it gives a snapshot of the factory rather than an authentic image which is always valid. To validate the data, numerous GEMBA walks, and observations were done at the production facility to get the most accurate picture. Due to confidentiality, the C-VSM of Company X was blurred and the information in the data boxes was altered. Figure 4.7 illustrates Company X Current State Value Stream Map. The given C-VSM is just to show the complexity of the production plant. It is evident that a push system is being used by Company X, which should be changed to a pull system. Furthermore, C-VSM illustrates that almost all the workstations are working as independent silos. This silo thinking should be eliminated to make the production plant leaner.

Similarly, F-VSM was made for Company X however it is not sown in this research due to confidentiality agreement signed with Company X.

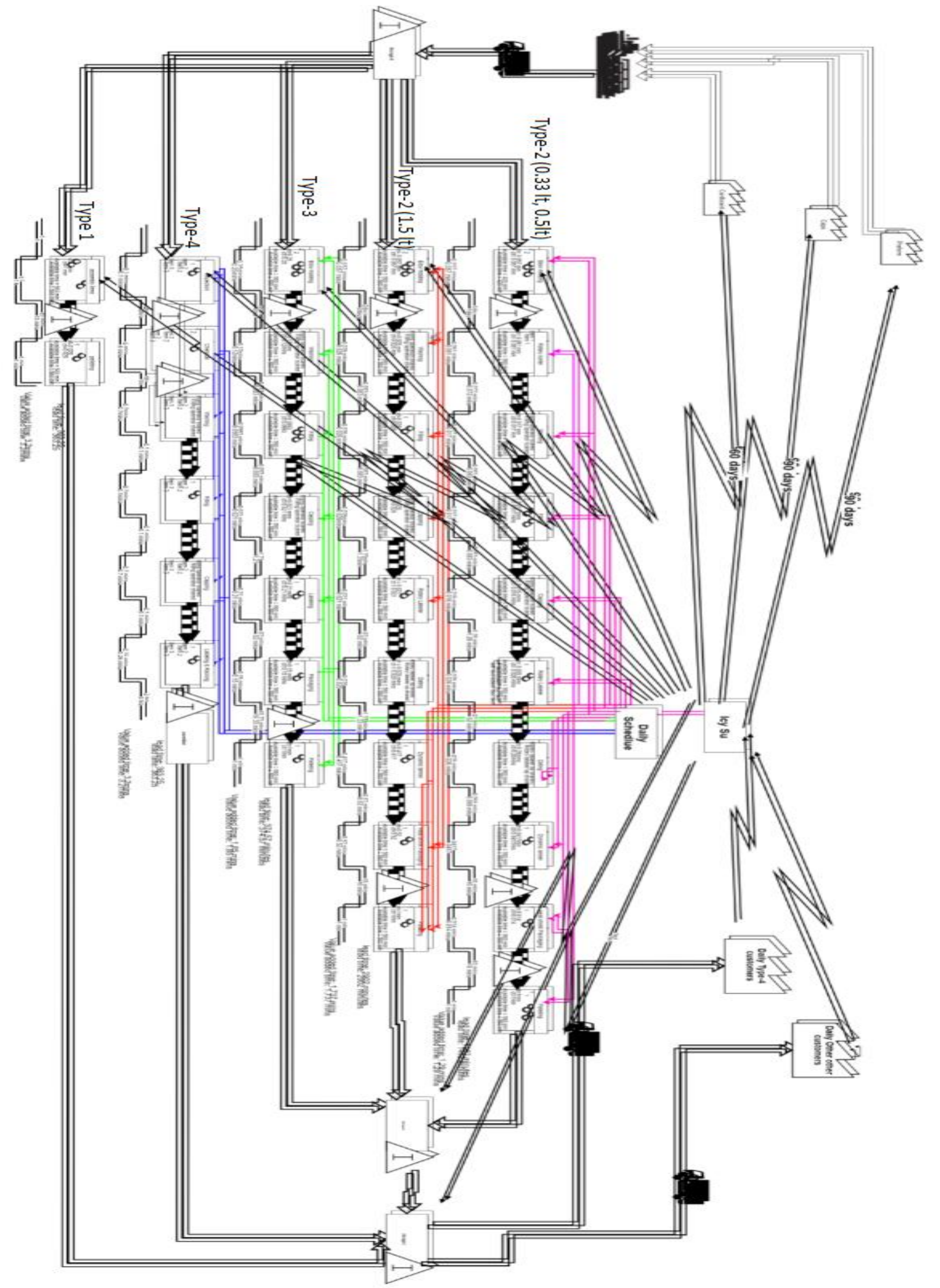


Figure 4.7. Company X Current State Value Stream Map (Blurred due confidentiality agreement)

4.4 **LSLP Stage 3: General layout**

4.4.1 Activity Relationship Chart (ARC)

Activity Relationship Chart (ARC) is one of the key tools used in LSLP to investigate the relationships present in between different machines, departments and assembly lines. The proximity relation between machines, departments, and assembly lines in ARC are represented by proximity/closeness rating and a numerical code. The code denotes the reason for the proximity/closeness. Table 4.4 summarizes the proximity/closeness rating, and Table 4.5 shows the key for the numerical code used in the Company X ARC. Figure 4.8 shows the ARC of Company X.

Table 4.4. ARC proximity/closeness rating

Rating	Proximity/Closeness
A	Absolutely necessary
E	Especially important
I	Important
O	Ordinary
U	Unimportant
X	Undesirable

Table 4.5. ARC Key

Numerical code	Reason
1	Breakdown and Repairs
2	Health and Safety
3	Vibrations
4	Controlled environment
5	Quality
6	Material handling cost

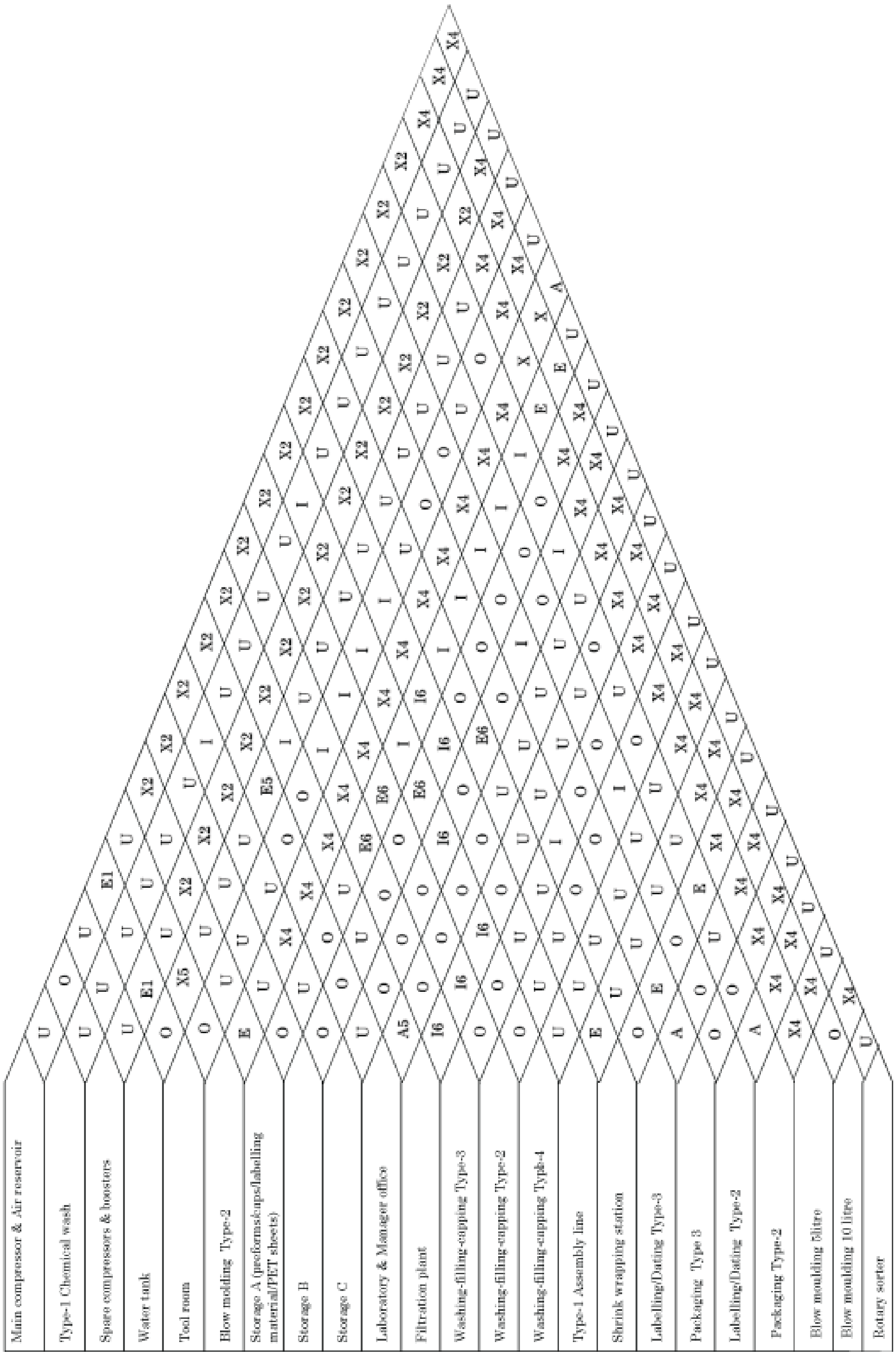


Figure 4.8. Activity relationship chart of Company X

4.4.2 Flow data

Product-machine and production volume matrix is one of the most important part of quantitative analysis for facility layout planning. This matrix not only illustrates the machines used in production of each product but also indicates the sequence of machines used, quantity of production, batch sizes and most importantly, the total number of trips made to meet the desired production demand of each product. Departments with the maximum number of trips should ideally be placed in close proximity. Table 4.6 shows the Product machine and production volume matrix of Company X.

Table 4.6. Product-machine and production volume matrix

	Machine															
Product		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**J**	**Production quantity**	**Batch size**	**Trips**
250ml water bottles	**1**	0	0	0	0	0	0	0	0	1	0	0	0	660	110	6
0.3 litre water bottles	**2**	1	0	0	2	0	0	3	0	0	4	0	4	10000	1200	9
0.5 litre water bottles	**3**	1	0	0	2	0	0	3	0	0	4	0	4	20000	720	28
1.5 litre water bottles	**4**	1	0	0	2	0	0	3	0	0	4	0	4	15000	240	63
5 litre water bottles	**5**	0	1	0	0	2	0	0	3	0	0	4	0	1000	72	14
10 litre water bottles	**6**	0	0	1	0	2	0	0	3	0	0	4	0	200	36	6
19 litre water bottles	**7**	0	0	0	0	0	1	0	0	0	0	0	0	4000	40	100

Product-machine and production volume matrix is used to obtain the To-From matrix. To-From matrix is used for assessing the closeness of different departments with each other and the location of the department on the production floor. Departments with maximum flows are kept in close proximity to minimize material handling costs, reduce emissions, and improve production quality. This matrix is also used for LSLP CRAFT layout design. Table 4.7 shows the To-From matrix of Company X.

Table 4.7. To-From matrix

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
A	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0
B	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
D	63	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0
E	0	14	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0	0	0	0	0	0	95	0	0	5
G	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
J	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0	0	6	100	20	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0	0	0	0	6	0	0	100	0	0
O	0	0	0	0	0	100	0	0	0	0	0	120	0	6	0	0	0
P	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0

To-From is the matrix that is utilized to make Flow matrix. Flow matrix is essential for making a dual graph. Table 4.8 shows the Flow matrix of Company X.

Table 4.8. Flow Matrix

	A	**0**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
A	0	0	0	63	0	0	0	0	0	0	0	0	100	0	0	37	0
B	0	0	0	0	14	0	0	0	0	0	0	0	14	0	0	0	0
C	0	0	0	0	6	0	0	0	0	0	0	0	6	0	0	0	0
D	63	0	0	0	0	0	100	0	0	0	0	0	0	0	0	37	0
E	0	14	6	0	0	0	0	20	0	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0	0	0	0	0	0	95	100	0	5
G	0	0	0	100	0	0	0	0	0	100	0	0	0	0	0	0	0
H	0	0	0	0	20	0	0	0	0	0	20	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0	0	6	6	0	0	0	0
J	0	0	0	0	0	0	100	0	0	0	0	100	0	0	0	0	0
K	0	0	0	0	0	0	0	20	0	0	0	20	0	0	0	0	0
L	0	0	0	0	0	0	0	0	6	100	20	0	0	6	120	0	0
M	100	14	6	0	0	0	0	0	6	0	0	0	0	0	0	0	0
N	0	0	0	0	0	95	0	0	0	0	0	6	0	0	106	0	5
O	0	0	0	0	0	100	0	0	0	0	0	120	0	106	0	0	0
P	37	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	0
Q	0	0	0	0	0	5	0	0	0	0	0	0	0	5	0	0	0

4.5 LSLP Stage 4: Detailed Layout

4.5.1 Dual Graph

Flow matrix is used to form planer adjacency graph and dual graph of Company X production plant. Figure 4.9 shows the planer adjacency graph and the dual graph of the current facility. Each black circular node represents a specific department whereas, the lines called edges and arcs, represent the flow from one department to another. In this dual graph of Company X production facility, the red lines signify there is no flow in-between nodes, whereas the black straight lines with the number on the lines, indicate the flow and the frequency of the flow. The curved line on top of the dual graph form summarizes the size of each department and are shown in figure A.2, Appendix A. Table 4.9 shows the area of each department. Departments with the maximum frequency of trips are explicitly represented on the dual graph and hence are placed first during the layout modelling phase.

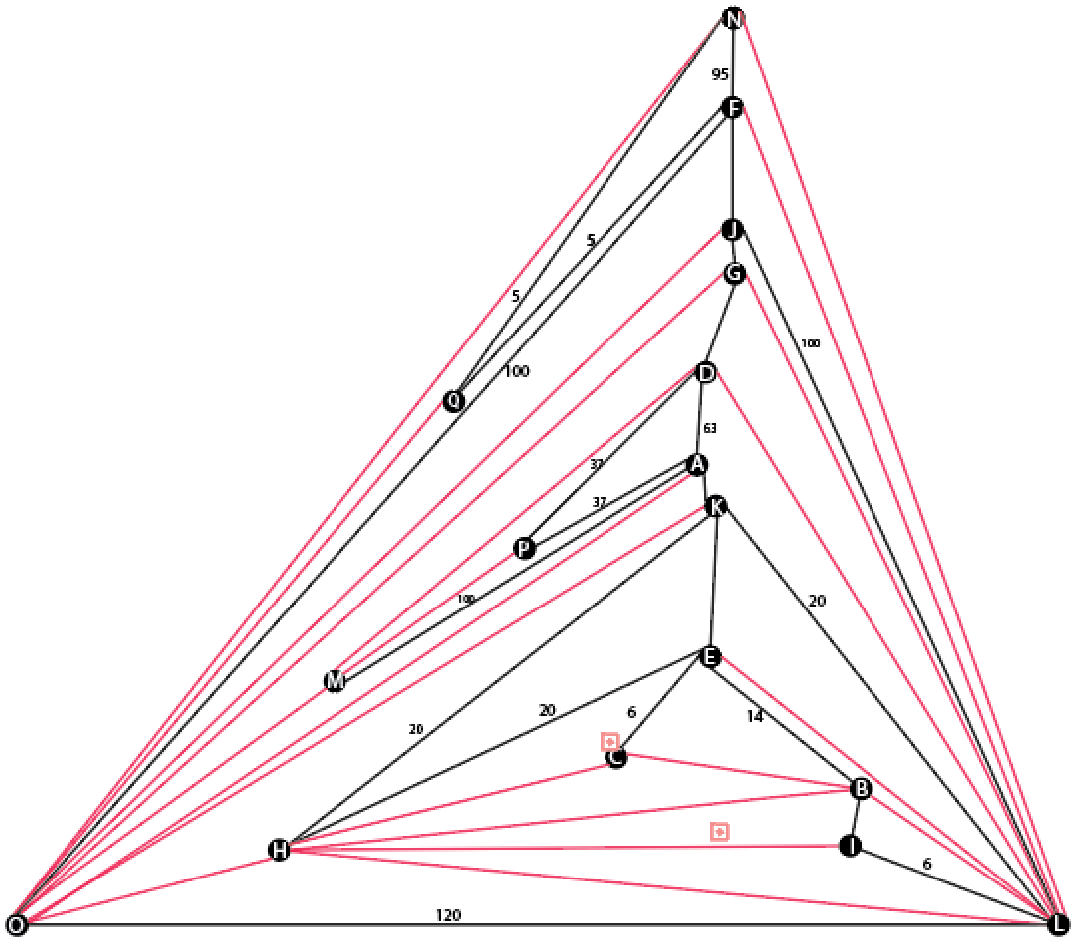


Figure 4.9. Dual graph of Company X

Table 4.9. Area of departments

Department number	**Department name**	**Machine**	**Area (m^2)**
D 1	**A**	Type-2 blow moulding machine	42
D 2	**B**	5 litre blow moulding machines	22
D 3	**C**	10 litre blow moulding machines	22

D 4	**D**	Type-2 litre cleaning, filling and capping machines	78
D 5	**E**	Type-3 Washing, filling and capping machines	40
D 6	**F**	Type-4 cleaning, filling and capping machines	80
D 7	**G**	Type-2 labelling machine and dating machine	75
D 8	**H**	Type-3 labelling machines	30
D 9	**I**	Type-1 assembly machine	50
D 10	**J**	Type-2 packaging machine	40
D 11	**K**	Type-3 litre packaging machines	18
D 12	**L**	Shrink wrapping station	15
D 13	**M**	Storage A (preforms/caps/labelling material/PET sheets)	225
D 14	**N**	Storage B	410
D 15	**O**	Storage C	230
D 16	**P**	Rotary sorter	32
D 17	**Q**	Type-2 Washing Station	25

4.5.2 SLP relationship chart

Activity Relationship chart, Flow data, spaghetti diagram and the dual graphs are used to form the SLP relationship diagram which will aid in not only assessing the current production facility but also in developing the lean layout for Company X.

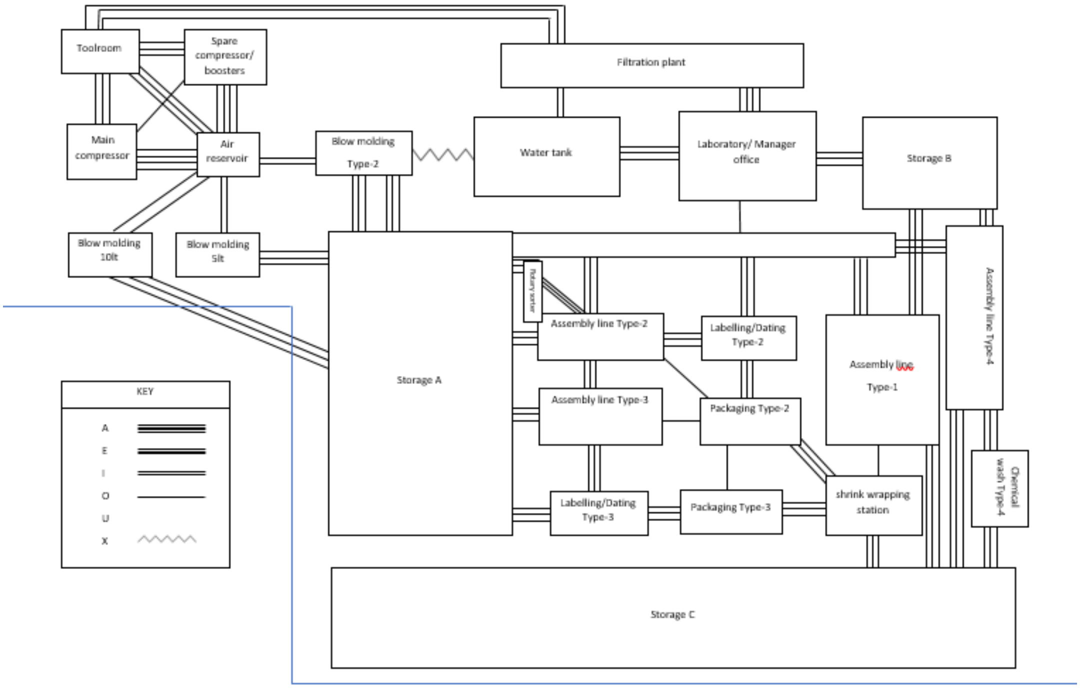


Figure 4.10. SLP relationship chart

CHAPTER 5

LSLP-GTA BASED PROPOSED LAYOUT

The LSLP-GTA based proposed layout is fabricated upon all the data gathered in LSLP Stage-2 and Stage-3. In this layout, all the departments are of the same size as the existing manufacturing plant. However, the locations are changed to minimize the MHD costs, emissions, and the distance travelled by the products. The layout is planned in a way that overcomes the current issues of the manufacturing plant. Compared to the existing layout, the total distance travelled by the goods is reduced by 16.68%, the net MHD cost reduced by 17.74%, while the MHD emission rating improved by 14.52%: Calculation of these is discussed in detail in Chapter 5. Figure 5.1 shows the 2D AutoCAD mechanical model, and Figure 5.2 shows the 3D Autodesk inventor model of the proposed layout.

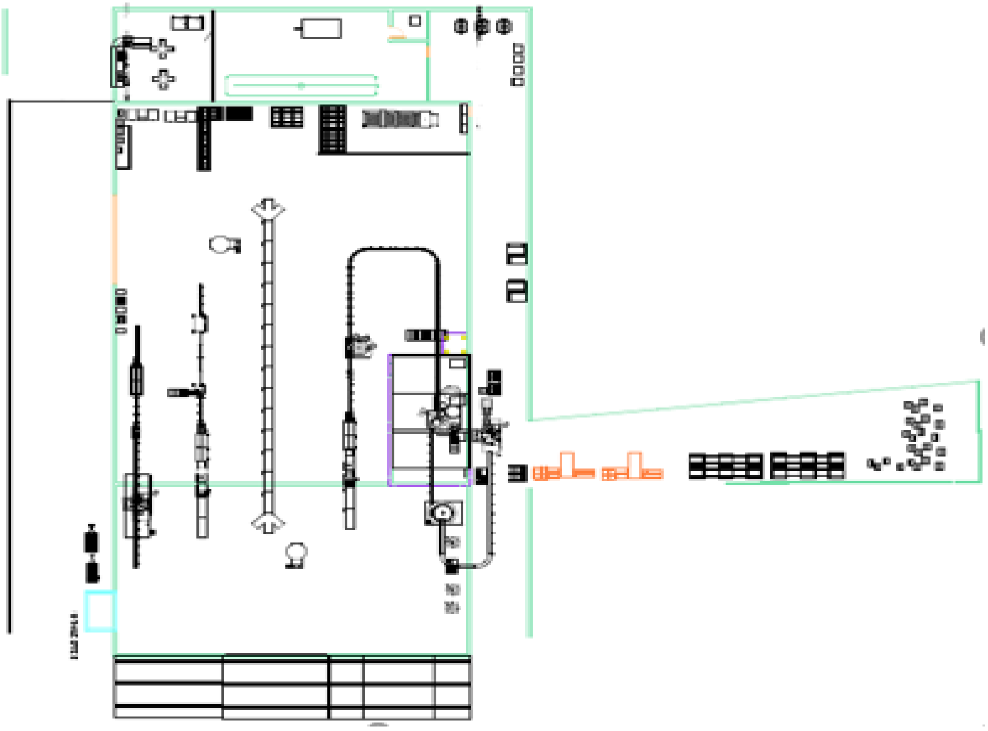


Figure 5.1. LSLP-GTA based layout 2D AutoCAD model

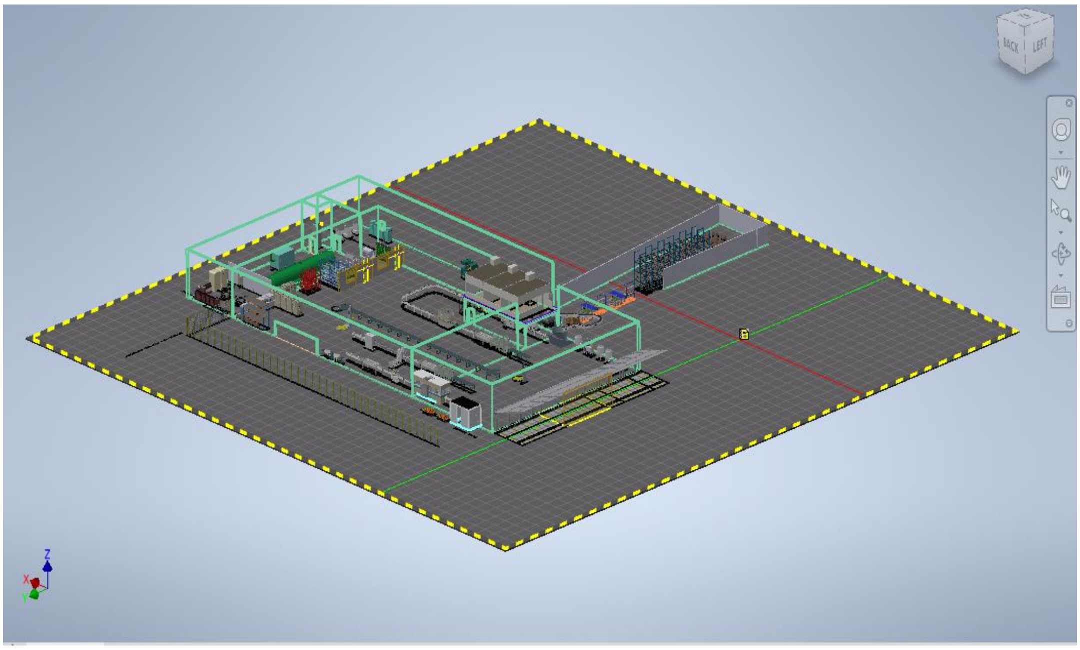


Figure 5.2. LSLP-GTA based layout 3D Autodesk inventor model

Storages

The LSLP-GTA based proposed layout has four main storages as shown in Figure 32. Storage A is for raw materials and emergency empty bottles stock. Storage B and Storage C have separate pallet wrapping stations to minimize transportation and motion wastes. A belt conveyor is placed in the centre of the production plant to transport shrink-wrapped pallets in between storage B and storage C. This not only aids in minimizing congestion but also reduces transportation time and lead time. Storage B is placed at the back end of the plant for biweekly and Type-1 orders. Storage D is one of the most vital storage among all. It is specifically for Type-4 bottles; this will aid in minimizing congestion.

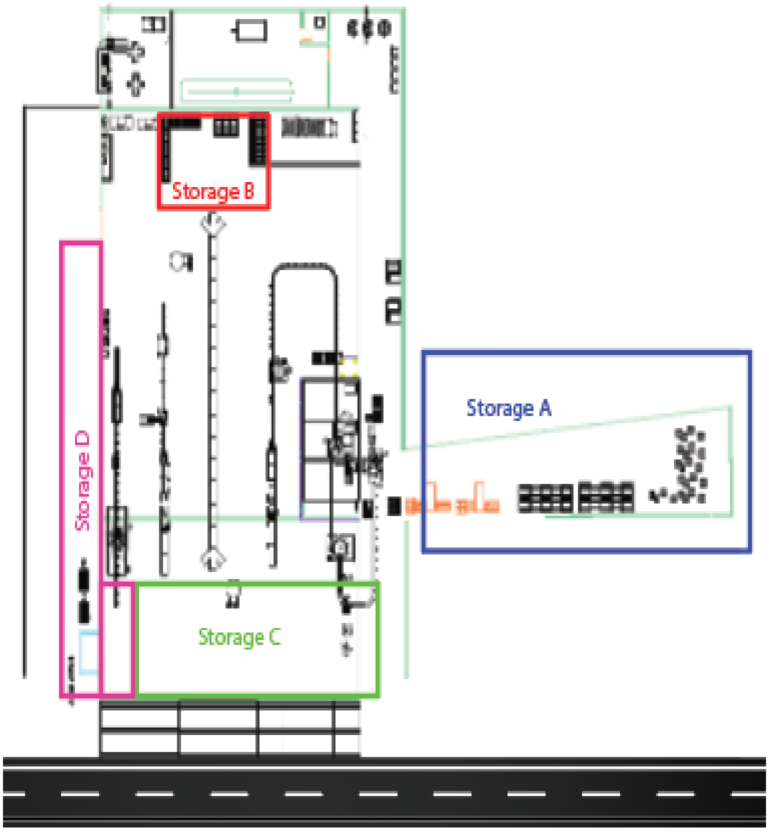


Figure 5.3. LSLP-GTA Storages

Entry and exit points

One of the most significant issues of the current production plant is congestion caused due to a single entry and exit point for all the products produced at Company X. The proposed layout has two strategically placed entry points and three exit points as shown in Figure 5.4. Entry 2 is primarily for raw materials for bottle production which will be stored in storage A. Raw materials can be unloaded from trucks and stored directly in storage A. Entry-1 and Exit-2 are solely for Storage D. Exit-3 is for Storage B whereas, Exit-1 is for daily orders stored in Storage C.

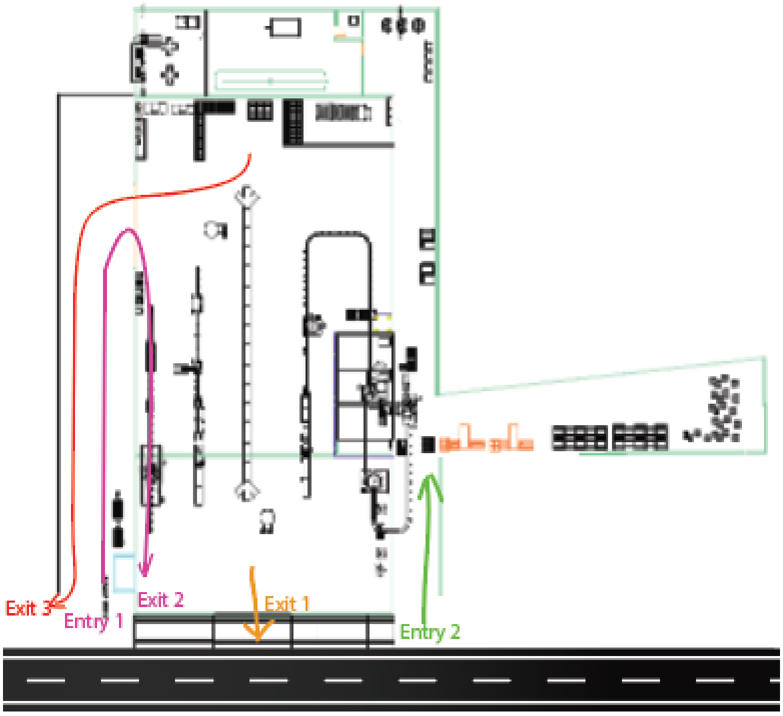


Figure 5.4. LSLP-GTA Entry and Exit points

Type-1 Production line

Type-1 assembly line is placed top right of the production facility beside Storage B and the path to Storage A. This department has straight frame carton flow storage racks for effective and easy storage of produced goods. Figure 5.5 shows the 3D model of Type-1 assembly line. Type-1 products can be shipped out of the plant from Exit 3.

Figure 5.5. LSLP-GTA Type-1 production line

Type-2 production line

As mentioned in chapter 3, type-2 production quantity is the largest, and the location of the type 2 blow moulding machine cannot be changed. Hence, Type-2 machines are placed first in a manner such that, the distance travelled by Type-2 product is smallest. Department 4, Department 7, Department 10 and Department 16 are placed in the close vicinity of department 1 to minimize the non-value-added cost and time caused due to excess transportation. Upon examination it was revealed, it is essential for Company X to invest in blow moulding machines to overcome speed miss match between the Type-2 Blow moulding machine. Faulty blow moulding instigates a number of lean wastes such as, an increase in lead time, increase in number of defects, increase in transportation distance and increase in motion. Once the Type-2 blow moulding machine is fixed or replaced, air conveyor system can be utilized to fully automate the type 2 assembly, which will aid in minimising the wastes mentioned before. A U-shaped layout is planned so that as single worker can take charge of the washing, filling and capping station, the labelling and dating machines, and lastly, the packaging station. Once the bottles are packed, they can be pelleted and stored either in storage B or C, depending on the order quantity and the space available in storage. Figure 5.6 shows the 3-D model of Type-2 production line.

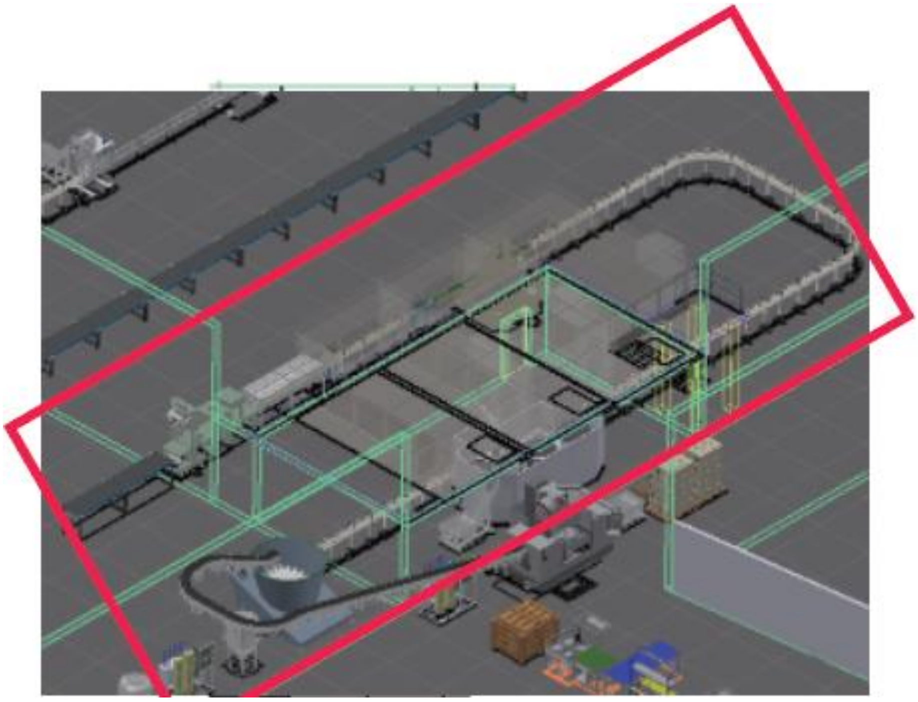


Figure 5.6. LSLP-GTA Type-2 production line

Type-3 production line

The production quantity of Type-3 products is lower compared to Type-2 and Type-4 products. Due to lower demand, number of trips of Type-3 are significantly lower compared to other product types. Based on this, it can be presumed the location of Type-3 production line is not as significant as the other production lines. Initial flow analysis emphasized that the Type-3 blow moulding machines should be placed close to the wall with substantial ventilation for H&S reasons. Due to this, Type-3 blow moulding machines are placed on the top left of the production facility close to the main door. Empty bottles can be stored in storage racks or storage B. They will be manually transported to Type-3 production line. Type-3 production line is parallel to Type-4 production line so single multi-skill personnel can take charge of Type-4 washing, filling and capping machine, and Type-3 washing, filling and capping machine, dynamic lanner, and the packaging machine. Once packed, another worker can use the pallet wrapping station to pallet the produced goods and send them to storage accordingly. Figure 5.7 shows the 3D model of Type-3 assembly line.

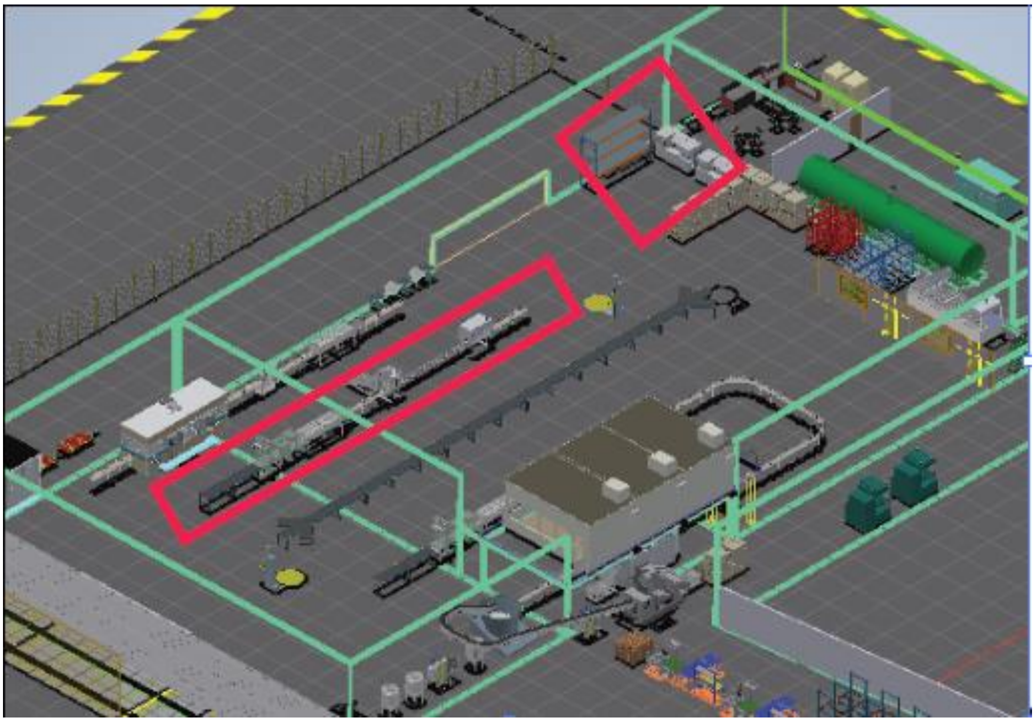


Figure 5.7. LSLP-GTA Type-3 production line

Type-4 Production line

Based on previous findings, Type-4 is the major cause of congestion in the current layout. Type-4 has the maximum number of daily trips and should be strategically placed so that the trips do not interfere with the rest of the production facility. Furthermore, 5% of the Type-4 bottles need to be washed with chemicals hence the chemical wash station should be placed closed to it. Lastly, the chemical wash station should be segregated and placed close to the walls to minimize health and safety risk. Due to these reasons, Type-4 production line is located close to the left wall of the production facility. A separate Exit is made explicitly for Type-4 bottle production to minimize congestion. Figure 5.8 shows the 3D model of type 4 production line and the chemical wash station.

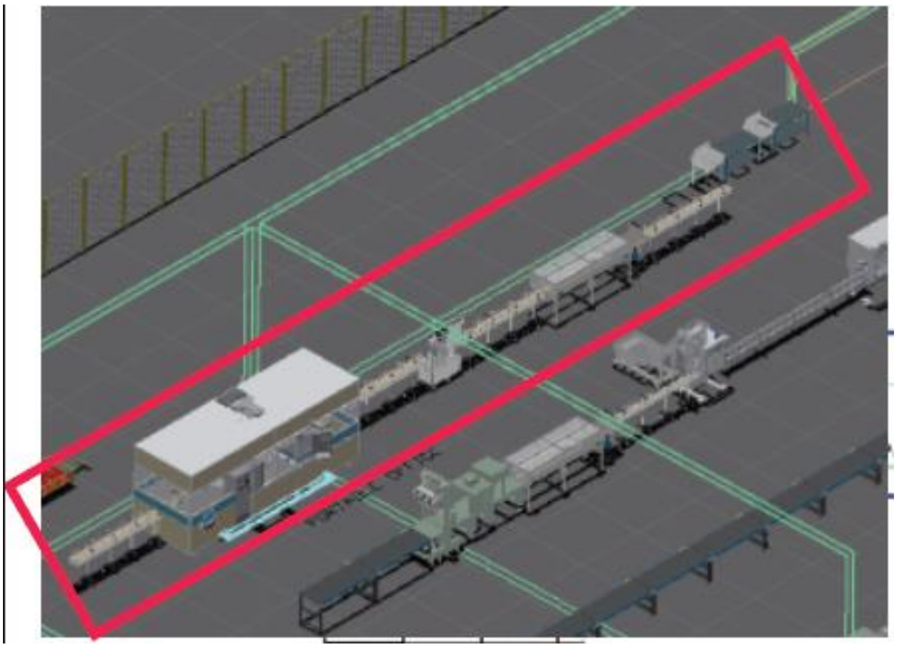


Figure 5.8. LSLP-GTA Type-4 production line

Break room

Based on discussion with the workers of the current manufacturing plant, Company X lacks facilities such as breakrooms. The facilities are essential to improve employee’s morale and productivity, which in turn aids in improving production quality as well. Kitchen and restrooms are located at the far corner of the production facility so that it does not negatively affect the flow of production. Figure 5.9 illustrates the Break room; this break room has restrooms, coffee machines and a kitchen to warm up homemade meals brought by employees.

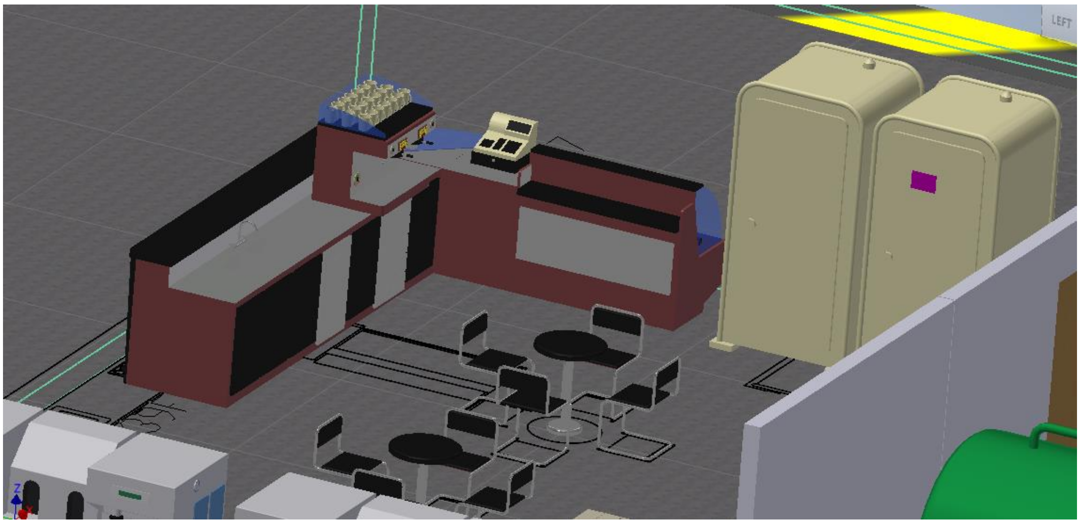


Figure 5.9. LSLP-GTA break room

CHAPTER 6

LAYOUT DESIGN IMPROVEMENT THROUGH CRAFT

As mentioned in Chapter 2, Computerized Relative Allocation of Facilities Technique (CRAFT) is one of the most well-known and robust algorithm used for facility layout planning. CRAFT excel plugin developed by Paul Jenson was used in this research. However, it had certain limitations which were catered to.

Firstly, CRAFT can only carry out pairwise exchanges if the departments are adjacent or are of equal size. It is limited in this extent that non-adjacent departments with different sizes cannot be exchanged by CRAFT. In order to overcome this limitation, multiple layouts were manually generated based on the work done in Chapters 3 and 4, and then used as input for CRAFT algorithm.

Secondly, production facility designed with CRAFT is solely dependent on minimizing the cost incurred during transport. It does not use multiple objectives such as emissions, or the total distance travelled by the goods, which could be of vital importance to the manufacturer. In order to overcome this, the cost equation was amended to calculate a score for MHD during transport emissions of each layout, as shown in Equation (6.1).

$$min\ E = \sum_{i=1}^{n} \sum_{j=i+1}^{n} f_{ij}\ e_{ij}\ d_{ij} \tag{6.1}$$

Where

E: Net MHD Emissions

f_{ij} : Frequency of trips/flow rate

e_{ij} : MHD emissions during the transfer from i to j

d_{ij} : Centroid distance from i to j

Data for the exact cost of transportation and MHD emissions on each route were not available hence, a relative scale was made based on the interviews with the management and the staff at the production facility. This research categorized the cost level as insignificant, low, medium, high, and highest transport cost. The cost level index of each trip is also dependent on physical factors such as the weight and the volume of the product being transported. Details of the cost level index are in Appendix B. The cost level index was later utilized to develop To-From cost matrix for CRAFT algorithm.

Table 6.1. To-From Cost level matrix

	D 1	D 2	D 3	D 4	D 5	D 6	D 7	D 8	D 9	D 10	D 11	D 12	D 13	D 14	D 15	D 16	D 17
D 1	■												1				
D 2		■											1				
D 3			■										1				
D 4	1			■												2	
D 5		2	2		■												
D 6						■								4			4
D 7				3			■										
D 8					4			■									
D 9									■				1				
D 10							3			■							
D 11								4			■						
D 12									3	3	5	■					
D 13													■				
D 14												5		■	5		
D 15						5						5		5	■		
D 16	1															■	
D 17														5			■

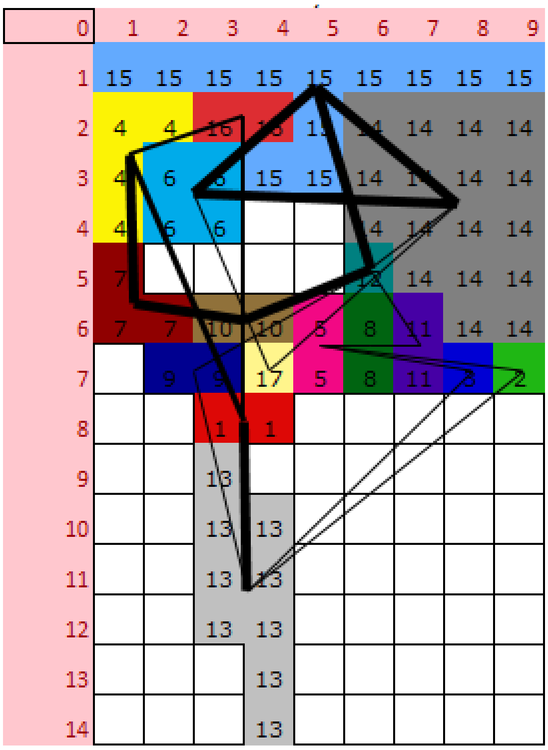
Similarly, MHD emissions level for each route were categorized as low, medium and high. The MHD emissions level index of each trip is also dependent on two more factors i.e., the type of equipment and the type energy used to transport the goods. Details of MHD emissions level index are in Appendix B. The MHD emission level index was later utilized to develop To-From emissions level matrix as shown in Table 6.2.

Table 6.2. To-From MHD emissions level matrix

	D 1	D 2	D 3	D 4	D 5	D 6	D 7	D 8	D 9	D 10	D 11	D 12	D 13	D 14	D 15	D 16	D 17
D 1	■												1				
D 2		■											1				
D 3			■										1				
D 4	1			■												5	
D 5		1	1		■												
D 6						■								2			2
D 7				4			■										
D 8					5			■									
D 9									■				2				
D 10							3			■							
D 11								2			■						
D 12									2	2	2	■					
D 13													■				
D 14												2		■	2		
D 15						2						2		2	■		
D 16	2															■	
D 17														1			■

6.1 CRAFT-Current layout

Firstly, current layout of the facility was used as the input for the CRAFT algorithm with the two newly added parameters to develop the base case, which could later be used for comparison. A scale of 5 m/unit was used on the 17 departments, which had a flow of goods to simplify and streamline the calculations. Department information such as the cells occupied by each department and the centroid of each department of the current layout is given in Appendix C. Rectilinear distance was used as a measure of total distance travelled by products being manufactured at Company X. Figure 6.1 illustrates the current layout of the 17 main departments which have flow of products at Company X. The thickness of the lines on the figure represents the frequency of flow. Thicker lines represent comparatively larger flow whereas, thinner lines represent lower flow. The total distance travelled is the sum of distance travelled by each product on each route. The total distance travelled by the goods in current plant layout is 4615m, the net MHD costs are 15015, while the Net MHD emission score is 9350. Table 6.3 tabulates the features of the existing production facility before CRAFT iterations.



0	1	2	3	4	5	6	7	8	9
1	15	15	15	15	15	15	15	15	15
2	4	4	16	16	15	14	14	14	14
3	4	6	6	15	15	14	14	14	14
4	4	6	6			14	14	14	14
5	7					12	14	14	14
6	7	7	10	10	5	8	11	14	14
7		9	9	17	5	8	11	3	2
8			1	1					
9			13						
10			13	13					
11			13	13					
12			13	13					
13				13					
14				13					

Figure 6.1. CRAFT Current layout graphical outcome

Table 6.3. CRAFT Current layout numerical outcome

Criteria	Current layout
Total distance travelled	4615 m
Net emission score	9350
Net cost	15015

Distance improvement with CRAFT-Current layout

A total of 6 iterations were carried out for distance minimization using CRAFT. Figure 6.2 illustrates the layout after distance minimization based on flow and location of departments. The total distance travelled by the goods was decreased by 8.9% and the net costs were reduced by 4.40%, while the Net MHD emission rating improved by 5.30%. Table 6.4 tabulates the features of the new layout after CRAFT iterations.

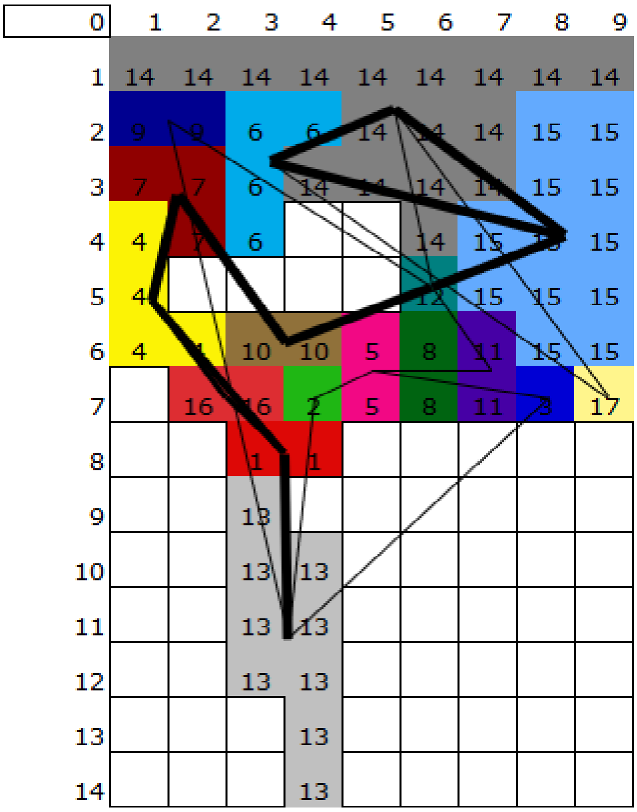


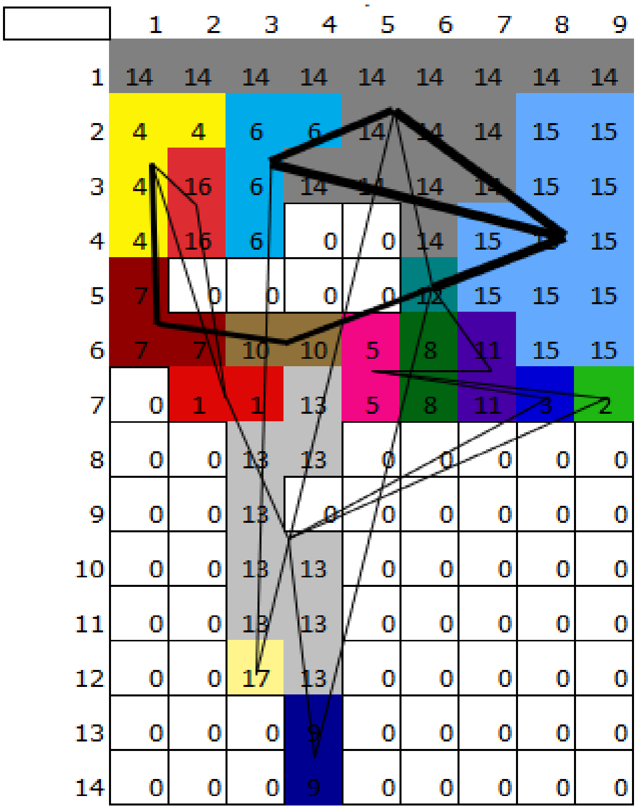
Figure 6.2. CRAFT Current layout distance minimization graphical outcome

Table 6.4. CRAFT Current layout distance minimization numerical outcome

Criteria	**Current layout**	**New layout**
Total distance travelled	4615 m	4202 m
Net MHD emissions	9350	8854
Cost	15015	14353

Cost improvement with CRAFT-Current layout

A total of four iterations were carried out for cost minimization of the current layout using CRAFT algorithm. Figure 6.3 illustrates the layout after cost minimization based on cost matrix, To-From flow matrix and the distance calculation. In this layout, even though the total distance travelled by the products was greater than the previous distance improvement case, however, the cost score was much lower. Compared to the existing layout, the total distance travelled by the goods decreased by 5.80%, the net MHD costs reduced by 6.78%, while the Net MHD emission rating improved by 7.48%. Table 6.5 tabulates the results of the production facility after cost minimization iterations.



	1	2	3	4	5	6	7	8	9
1	14	14	14	14	14	14	14	14	14
2	4	4	6	6	14	14	14	15	15
3	4	16	6	14	14	14	14	15	15
4	4	16	6	0	0	14	15	15	15
5	7	0	0	0	0	12	15	15	15
6	7	7	10	10	5	8	11	15	15
7	0	1	1	13	5	8	11	3	2
8	0	0	13	13	0	0	0	0	0
9	0	0	13	0	0	0	0	0	0
10	0	0	13	13	0	0	0	0	0
11	0	0	13	13	0	0	0	0	0
12	0	0	17	13	0	0	0	0	0
13	0	0	0	9	0	0	0	0	0
14	0	0	0	9	0	0	0	0	0

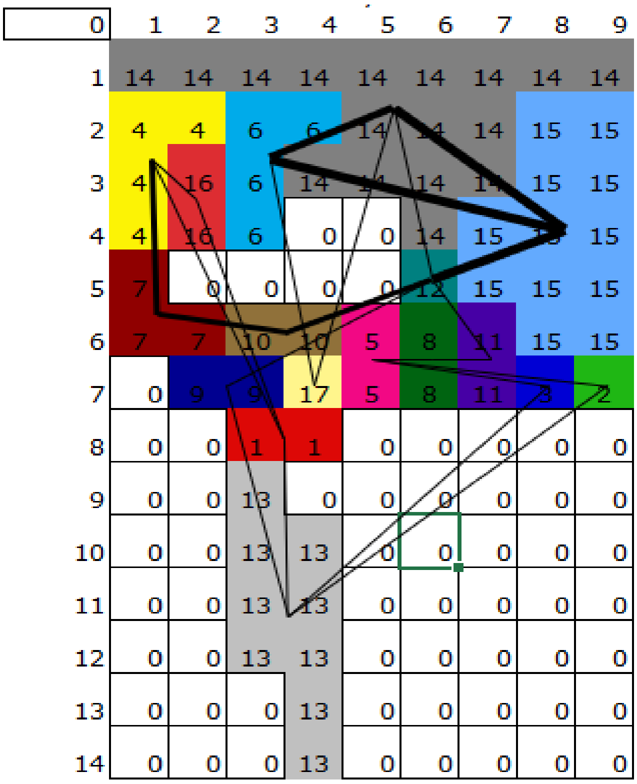
Figure 6.3. CRAFT Current layout cost minimization graphical outcome

Table 6.5. CRAFT Current layout cost minimization numerical outcome

Criteria	**Current layout**	**New layout**
Total distance travelled	4615 m	4346 m
Net MHD emissions	9350	8651
Cost	15015	13997

Emissions improvement with CRAFT-current layout

A total of five iterations were carried out for Net MHD emission minimization of current layout using CRAFT algorithm. Figure 6.4 illustrates the layout after emission minimization based on To-From emission matrix, To-From flow matrix and the centroid location. This layout produced the least MHD emissions compared to the previous 3 layouts. Compared to the existing layout, the total distance travelled by the goods improved by 8.71 %, the net costs reduced by 6.28 %, while the MHD emission rating improved by 9.48%. Table 6.6 tabulates the results of the production facility after MHD emission minimization iterations.



0	1	2	3	4	5	6	7	8	9
1	14	14	14	14	14	14	14	14	14
2	4	4	6	6	14	14	14	15	15
3	4	16	6	14	14	14	14	15	15
4	4	16	6	0	0	14	15	15	15
5	7	0	0	0	0	12	15	15	15
6	7	7	10	10	5	8	11	15	15
7	0	9	9	17	5	8	11	3	2
8	0	0	1	1	0	0	0	0	0
9	0	0	13	0	0	0	0	0	0
10	0	0	13	13	0	0	0	0	0
11	0	0	13	13	0	0	0	0	0
12	0	0	13	13	0	0	0	0	0
13	0	0	0	13	0	0	0	0	0
14	0	0	0	13	0	0	0	0	0

Figure 6.4. CRAFT Current emission minimization graphical outcome

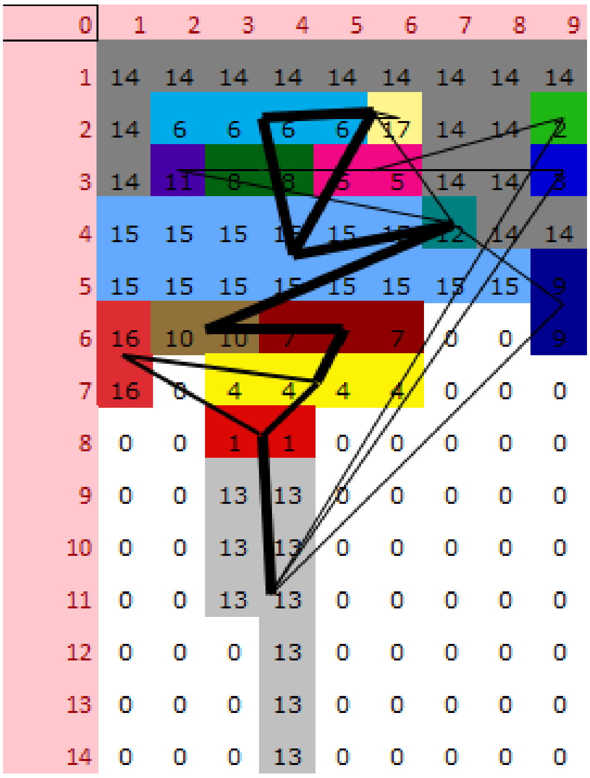
Table 6.6. CRAFT Current emission minimization numerical outcome

Criteria	**Current layout**	**New layout**
Total distance travelled	4615 m	4212 m
Net MHD Emissions	9350	8464
Cost	15015	14072

It is evident from the above current layout cases that there is a non-linear relationship between all three parameters. For example, even though the distance travelled by the assembly and subassemblies might be the local minimum, the net cost could still be greater.

6.2 CRAFT-LSLP GTA layout

Secondly, LSLP GTA layout was used as the input for the CRAFT algorithm. Table 6.5 tabulates the current parameters of LSLP GTA layout design before CRAFT iterations.



0	1	2	3	4	5	6	7	8	9
1	14	14	14	14	14	14	14	14	14
2	14	6	6	6	6	17	14	14	2
3	14	11	8	8	5	5	14	14	3
4	15	15	15	15	15	15	12	14	14
5	15	15	15	15	15	15	15	15	9
6	16	10	10	7	7	7	0	0	9
7	16	0	4	4	4	4	0	0	0
8	0	0	1	1	0	0	0	0	0
9	0	0	13	13	0	0	0	0	0
10	0	0	13	13	0	0	0	0	0
11	0	0	13	13	0	0	0	0	0
12	0	0	0	13	0	0	0	0	0
13	0	0	0	13	0	0	0	0	0
14	0	0	0	13	0	0	0	0	0

Figure 6.5. LSLP-GTA based layout

Table 6.7. LSLP-GTA based layout

Criteria	**Current layout**	**New layout**
Total distance travelled	4615 m	3844 m
Net MHD Emissions	9350	7992
Cost	15015	12351

Distance improvement with CRAFT- LSLP GTA layout

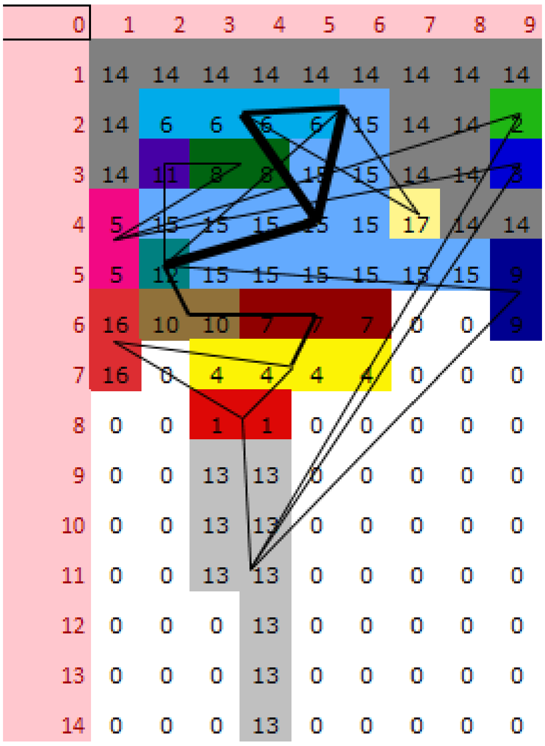
LSLP GTA layout distance could not be improved with CRAFT.

MHD emissions improvement with CRAFT- LSLP GTA layout

Similarly, CRAFT could not further minimize the MHD emission score based on To-From emission matrix, To-From flow matrix and the location of departments.

Cost improvement with CRAFT-Current layout

A total of four iterations were carried out for cost minimization starting with LSLP-GTA based layout as the initial parameter. Figure 6.6 illustrates the layout after cost improvement based on To-from flow matrix, cost matrix and the location of departments. Compared to the existing layout, the total distance travelled by the goods improved by 25.31 %, the net costs reduced by 27.43 % while the MHD emission rating improved by 23.21%. Table 6.8 summarizes the results of the production facility after cost minimization iterations.



0	1	2	3	4	5	6	7	8	9
1	14	14	14	14	14	14	14	14	14
2	14	6	6	6	6	15	14	14	2
3	14	11	8	8	15	15	14	14	3
4	5	15	15	15	15	15	17	14	14
5	5	12	15	15	15	15	15	15	9
6	16	10	10	7	7	7	0	0	9
7	16	0	4	4	4	4	0	0	0
8	0	0	1	1	0	0	0	0	0
9	0	0	13	13	0	0	0	0	0
10	0	0	13	13	0	0	0	0	0
11	0	0	13	13	0	0	0	0	0
12	0	0	0	13	0	0	0	0	0
13	0	0	0	13	0	0	0	0	0
14	0	0	0	13	0	0	0	0	0

Figure 6.6. LSLP CRAFT-GTA Layout cost minimized

Table 6.8. LSLP CRAFT-GTA Layout cost minimized

Criteria	**Current layout**	**New layout**
Total distance travelled	4615 m	3446 m
Net MHD Emission	9350	7180
Cost	15015	10895

Even though the results produced by CRAFT using LSLP-GTA-Layout as the initial layout are far superior, the location of various departments is not ideal for the Company X production facility. Department 17 *'19 lt chemical wash'* is placed in the centre of the manufacturing facility, this could lead to health and safety risks in case of spillage. Ideally, it should be located near one of the walls and right beside Department 6 since a single operator loads the empty 19 bottles in the type-4 assembly line. Furthermore, transferring empty Type-3 bottles from blow moulding machines to Type-3 assembly line will cause congestion since they are located at the opposite end of the manufacturing plant. Air conveyor to remove congestion for such low production volume is not recommended due to high implementation cost.

6.3 **Layout evaluation**

Similarly, multiple layouts were manually generated using the data gathered in LSLP stage 2 and LSLP stage 3. These models were used as the initial layout that are later improved by CRAFT algorithm based on the three parameters mentioned previously in this chapter. Minor alterations were manually done to the layout to overcome the CRAFT limitations discussed before and to make the layout leaner. The final layout of the most efficient 10 results after CRAFT improvement are given in Appendix D. These 10 layouts are the final layouts that could not be improved further, no matter which parameter was chosen as the objective function.

Total distance travelled by the product is one of the most important parameters in lean facility layout planning. Reducing the total distance travelled minimises lean wastages such as lead time, transport, waiting, and motion. Furthermore, minimizing the distance travelled also improves the pace of production, which ultimately results in improved productivity and decreases the net cost of manufacturing. Figure 6.7 illustrates the distance travelled versus the current and prospective future layout of Company X production facility. In the existing production plant, the total distance travelled by the goods is 4614 meters; this distance was minimized to 4202 meters using CRAFT. Whereas the total distance travelled by the goods in *LSLP-GTA based* layout is 3844 meters, this distance is minimized to 3446 meters using CRAFT algorithm. The total distance travelled by goods in *LSLP CRAFT-Layout 7* is 2998 meters, which is the lowest among the 16 final layouts shown in Figure 6.7. *LSLP CRAFT-Layout 7* showed an overall 35.02% reduction in the distance travelled compared to the current production facility of Company X.

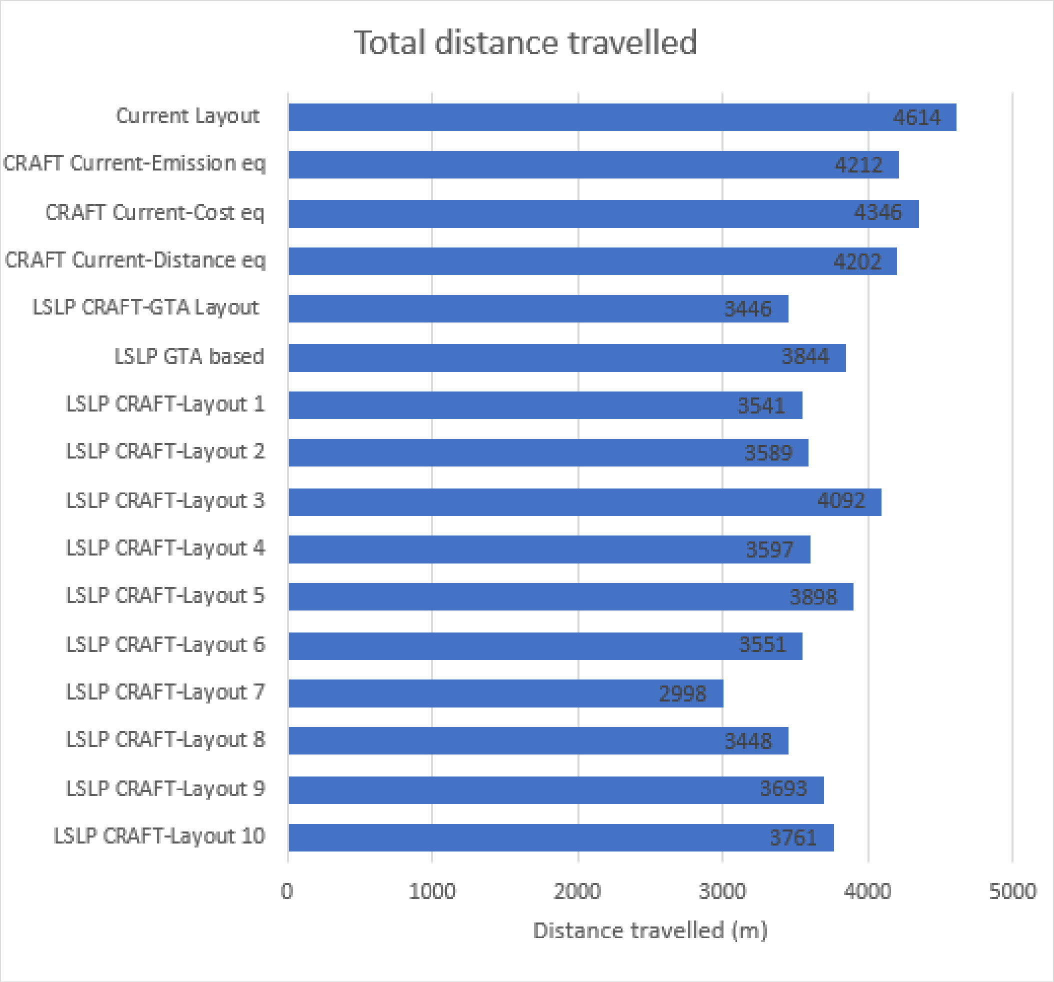


Figure 6.7. Total distance travelled by the products versus layouts

In the current era, manufacturing firms are constantly moving towards sustainable and greener production. Reducing total MHD emissions plays a vital role in the road to achieving sustainability. Figure 6.8 illustrates the MHD emissions of the current and the future prospective layouts of Company X production facility. In this graph, lower number signifies lower emissions. Even though the distance travelled in *CRAFT Current-Distance eq* layout is lower than that of CRAFT *Current-Emission eq* layout, the net MHD emissions of *CRAFT Current-Distance* are larger than the CRAFT *Current-Emission eq*. This difference in MHD emissions supports the fact reducing the total distance travelled does not always result in reduced emissions. Figure 6.8 shows the current production plant has MHD emissions score of 8854; this is improved to 8464 using MHD emissions equation as the objective function in CRAFT algorithm. MHD emission score of *LSLP-GTA layout* is 7992, which is improved to 7180 using MHD emission equation as the objective function in CRAFT algorithm. The net emission in *LSLP CRAFT-Layout 7* is 5904, which is by far the best among the 16 layouts. LSLP CRAFT-Layout 7 showed an overall 36.86% reduction in the total emissions compared to the current production facility of Company X.

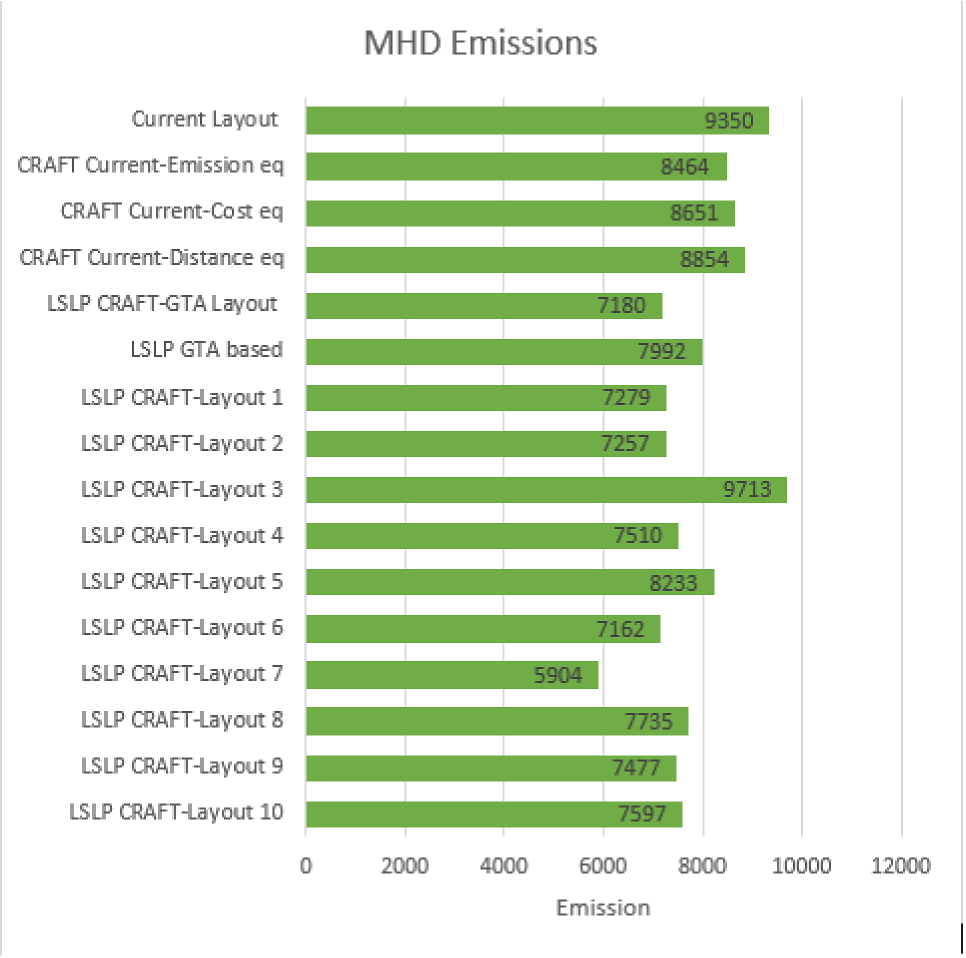


Figure 6.8. Net MHD emissions versus layout

Figure 6.9 illustrates the MHD costs of the current and prospective future layouts of Company X production facility. All the prospective LSLP-CRAFT based layouts significantly reduced the MHD costs. Even though, the distance travelled in *LSLP CRAFT-Layout 8* and *LSLP CRAFT-GTA Layout* is almost identical, there is a significant difference in MHD costs. MHD costs of *LSLP CRAFT-Layout 8* is 12168 and *LSLP CRAFT-GTA Layout* is 10895. This difference in cost indicates that the MHD costs are not solely dependent on distance and the location of the departments but also on MHD unit cost of a specific trip. The net MHD costs of the current production plant are 15015; this is improved to 13997 using the cost equation as the objective function in the CRAFT algorithm. MHD costs of LSLP-*GTA layout* is 12351, which is improved to 10895 using cost equation as the objective function in CRAFT algorithm. The MHD cost of *LSLP CRAFT-Layout 7* was 9452, which is by far the lowest amongst the 16 layouts shown in Figure 6.9. LSLP CRAFT-Layout 7 resulted in overall 37.05% reduction in the MHD cost compared to the current production facility of Company X.

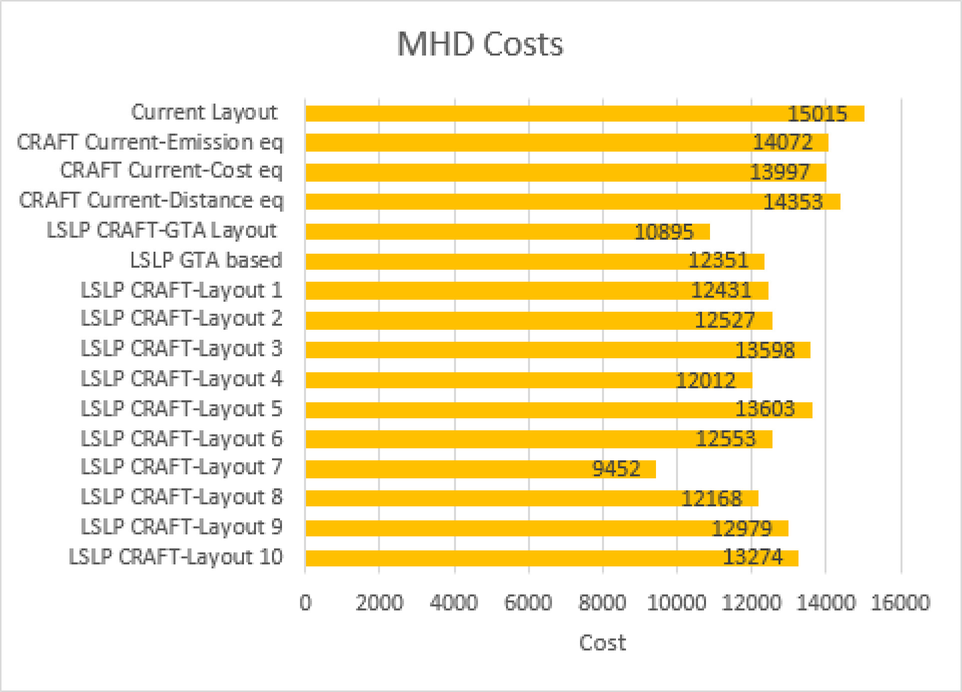


Figure 6.9. Net MHD Costs versus layout

6.4 CRAFT based proposed layout

Based on the aforementioned results, *LSLP CRAFT-Layout 7* dominates all other layouts as it is superior than all other layouts in all selected criteria. Thus, it should be chosen. Overall, compared to the *Current Layout*, the LSLP CRAFT-Layout 7 resulted in overall 35.02% reduction in distance travelled, 37.05% reduction in the

MHD cost, and 36.86% reduction in the total MHD emissions. Figure 6.10 shows the 2D AutoCAD mechanical model and Figure 6.11 3D Autodesk inventor factory CAD model of *LSLP CRAFT-Layout 7*.

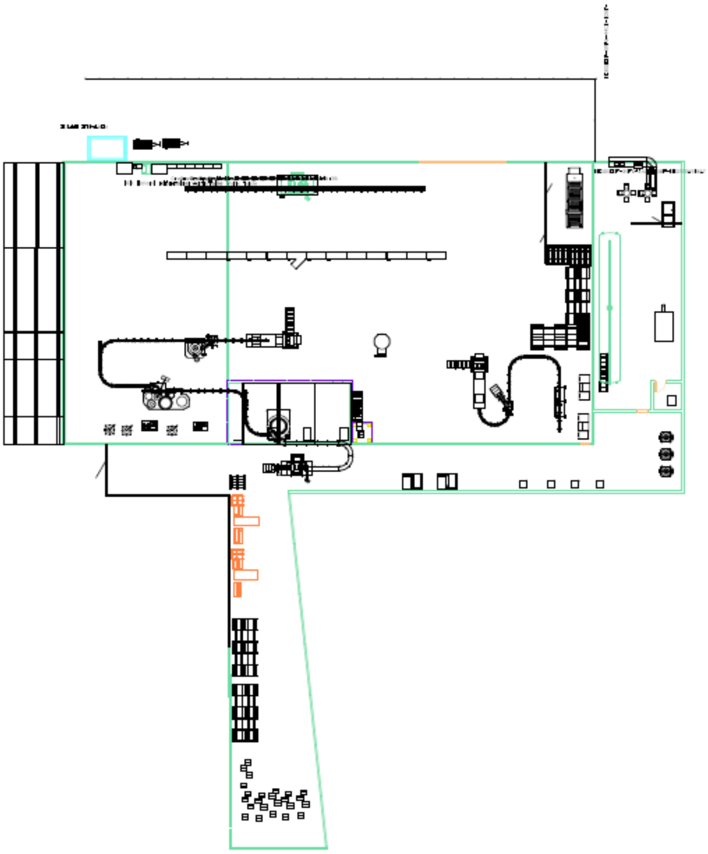


Figure 6.10. LSLP CRAFT-Layout 7 2D AutoCAD model

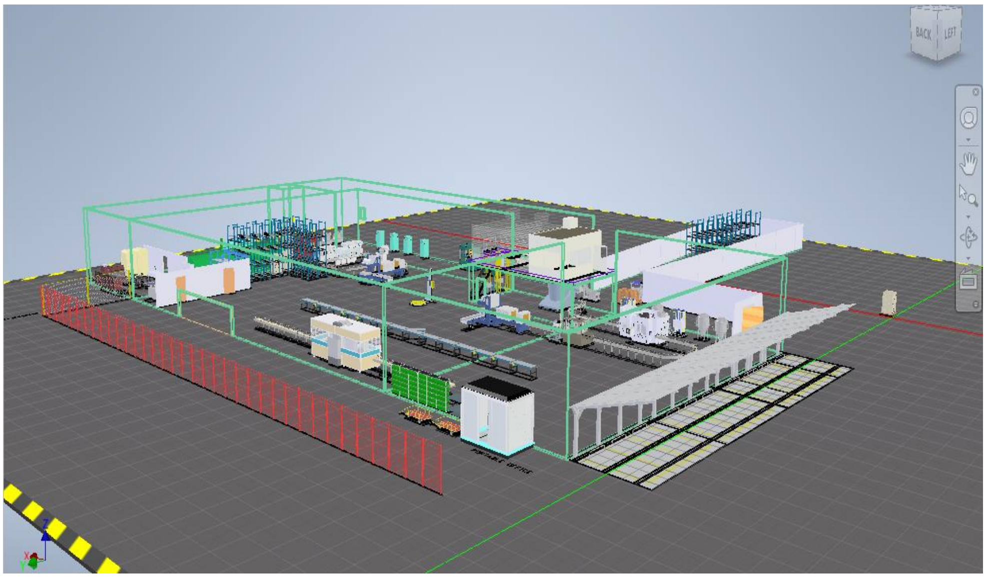


Figure 6.11. LSLP CRAFT-Layout 7 layout 3D Autodesk inventor model

Storages

The LSLP CRAFT-Layout 7 has five main storages, as shown in Figure 6.12. Storage A is for raw materials and emergency empty bottles stock. Belt conveyor is placed in the centre of the production plant to transport pallets in-between storage B, storage C and storage E. This will aid in not only minimizing congestion but also reducing transportation time. Storage B is placed at the back end of the plant for large orders, which take multiple days to be fulfilled. Storage D is one of the most vital storages among the five storages. It is specifically for Type-4 bottles; Filled bottles trolleys can be placed along the corridor to minimize congestion. During observation, it was observed that there was a queue for the pallet shrink wrapping station. Hence, Storage E is specifically for the pallet wrapping station. All the storage will be marked so that employees have a visual accord that is to be followed.

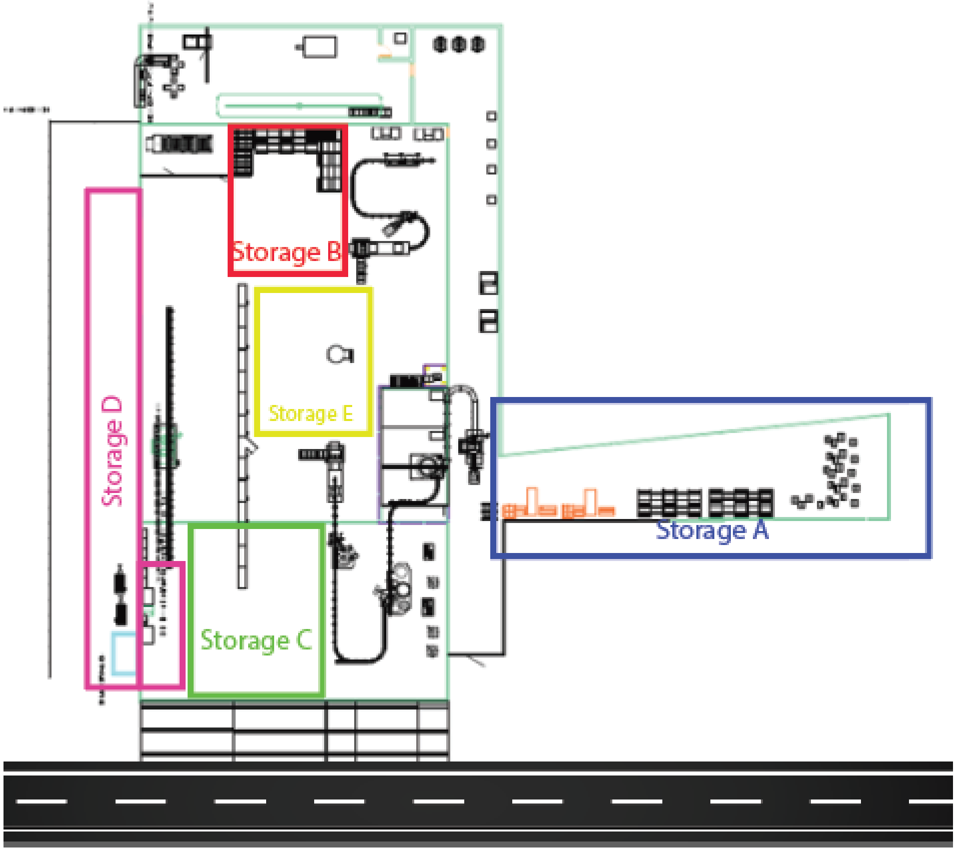


Figure 6.12. LSLP CRAFT-Layout 7 storages

Entry and exit points

One of the biggest issues of the current production plant is congestion caused due to single entry and exit point for all the products produced at Company X. The proposed layout has two strategically placed entry points and three exit points as shown in Figure 6.13. Just in time framework will be followed for Type-4 bottles; hence, Entry-1 and Exit-2 are solely for Storage D i.e., Type-4 water storage. Entry 2 is primarily for raw materials for bottle production, which will be stored in storage A. Entry-2 will minimize the transportation distance of the raw material and minimize congestion since the workers will not have to cross the entire plant to replenish raw materials. Exit-3 is for Storage B, so the goods can be directly shipped to the trucks via the corridor without the need to travel inside the plant. Lastly, Exit-1 is for daily orders stored in Storage.

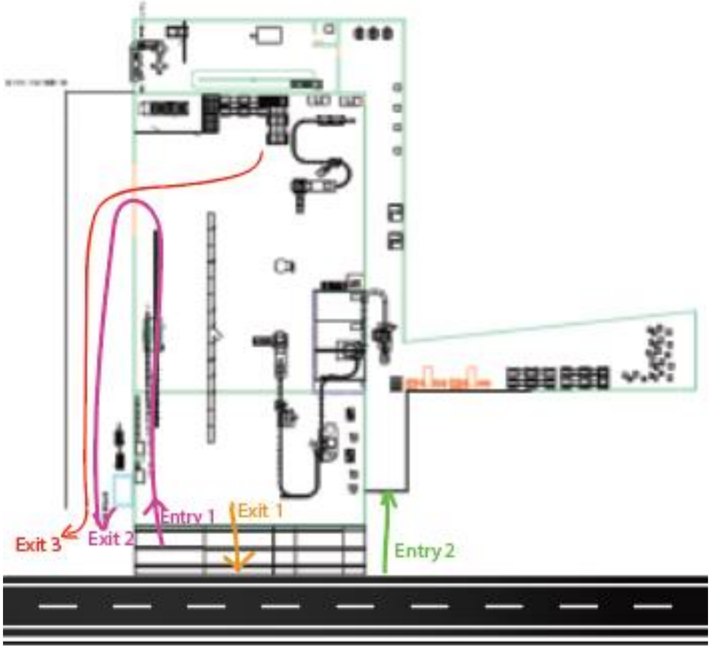


Figure 6.13. LSLP CRAFT-Layout 7 Entry and Exit points

Type-1 Production line

Type-1 production line is placed top left of the production facility beside Storage B. This department has straight frame carton flow storage racks for effective yet easy storage of produced goods. This production has designated entry and exit doors from the department to standardize the flow of floor men. Figure 6.14 shows the 3D model of Type-1 assembly line.

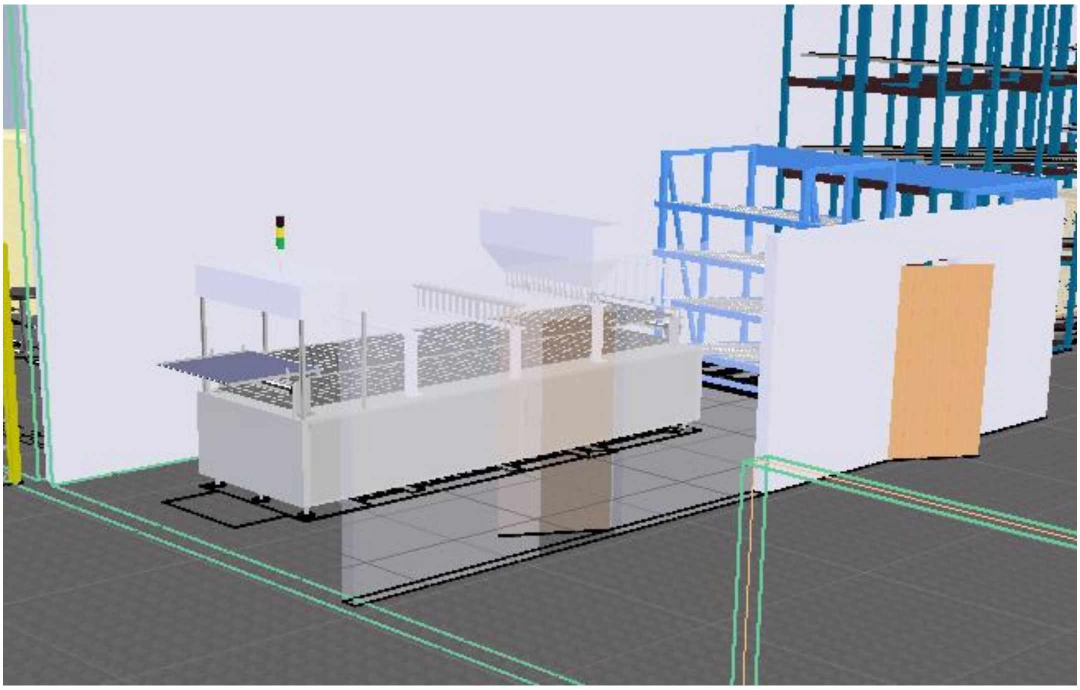


Figure 6.14. LSLP CRAFT-Layout 7 Type-1 Production line

Type-2 production line

Type-2 machines are placed first so that the distance travelled by Type-2 product is smallest. As mentioned before, Company X needs to invest in blow moulding machines to minimize transportation distance and motion by operating the air conveyor system. A U-shaped layout is planned so that as a single worker can take charge of the washing, filling and capping station, the labelling and dating machines, and lastly, the packaging station. Once the bottles are packed, they can be pelleted and stored either in storage B or storage C. Rotary sorter room underneath the laboratory can be used as a dedicated storage place for blow moulded Type-2 empty bottle stock. Depending on the type of order and the space available in storage, pallets can be shipped to Storage C or Storage B using a belt conveyor located in the centre of the production facility. Figure 6.15 shows the 3D model of Type-2 production line.

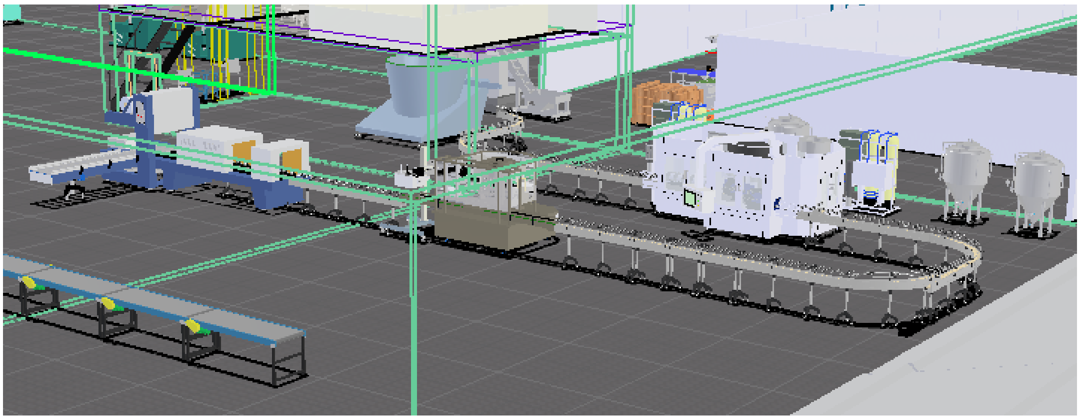


Figure 6.15. LSLP CRAFT-Layout 7 Type-2 Production line

Type-3 production line

As mentioned before, Type-3 litre blow moulding machines should be placed close to the wall with substantial ventilation for H&S reasons. Due to this, type-3 blow moulding machines are placed on the top right of the production facility. Type-3 empty bottles can be stored in dedicated racks beside the blow moulding machine. They will be manually transported to Type-3 production line, which is placed right beside the blow moulding machine by CRAFT algorithm to minimize distance travelled, emissions and cost. Type-3 production line is made in U type layout so that a single multi-skill personnel can take charge of Type-3 washing, filling and capping machine as well as labelling and dating machines. Lastly, packaging machines are oriented to minimize motion during pickup and distance travelled from the packaging machine to the pallet shrink wrap station. Once pelleted, Type-3 products can be shipped from Storage E to Storage B or Storage C depending on order type and space available in the storages. Figure 6.16 shows the 3D model of Type-3 assembly line.

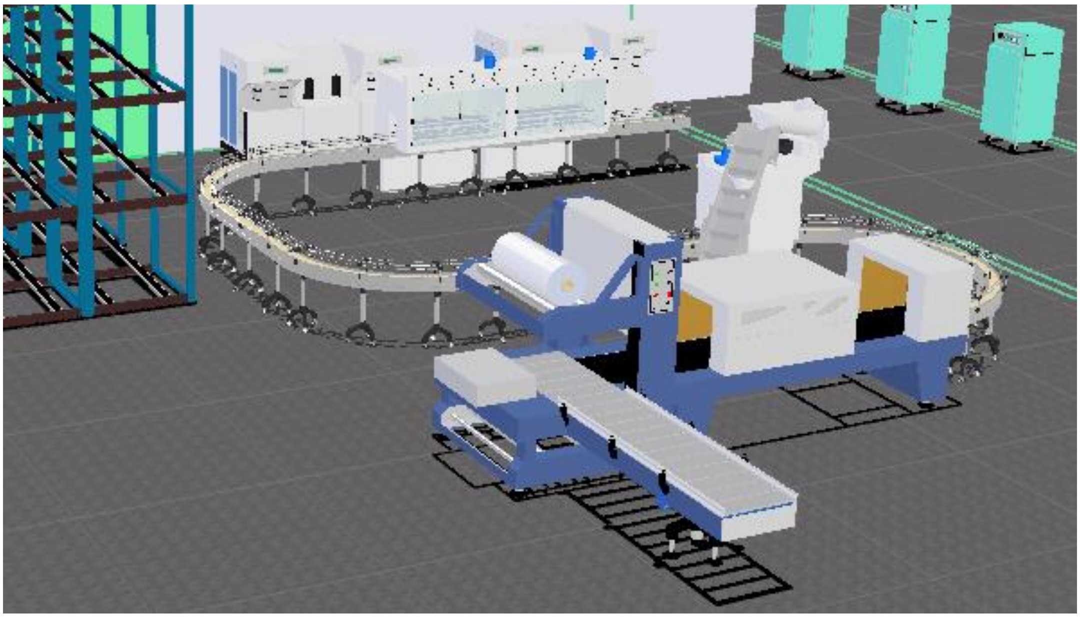


Figure 6.16. LSLP CRAFT-Layout 7 Type-3 Production line

Type-4 Production line

As mentioned before, Type-4 is the major cause of congestion in the current layout. A separate Exit and Entry are made explicitly for Type-4 bottle production to support Just in time production, eliminating congestion. Storage racks are placed at the chemical wash station for systematic storage of cleaned and contaminated empty bottles. Figure 6.17 shows the 3D model of Type-4 production line and the chemical wash station.

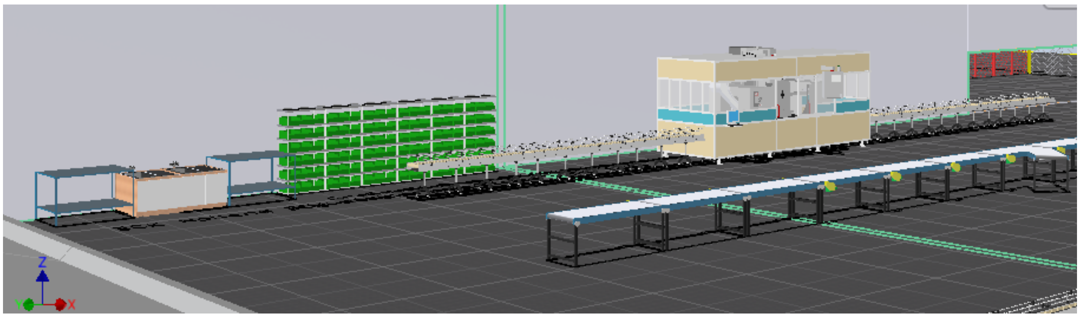


Figure 6.17. LSLP CRAFT-Layout 7 Type-4 Production line

Break room

For the reasons mentioned in LSLP-GTA based layout, a break room was made for employees in LSLP CRAFT-Layout 7. Figure 6.18 shows the 3D model of the break.

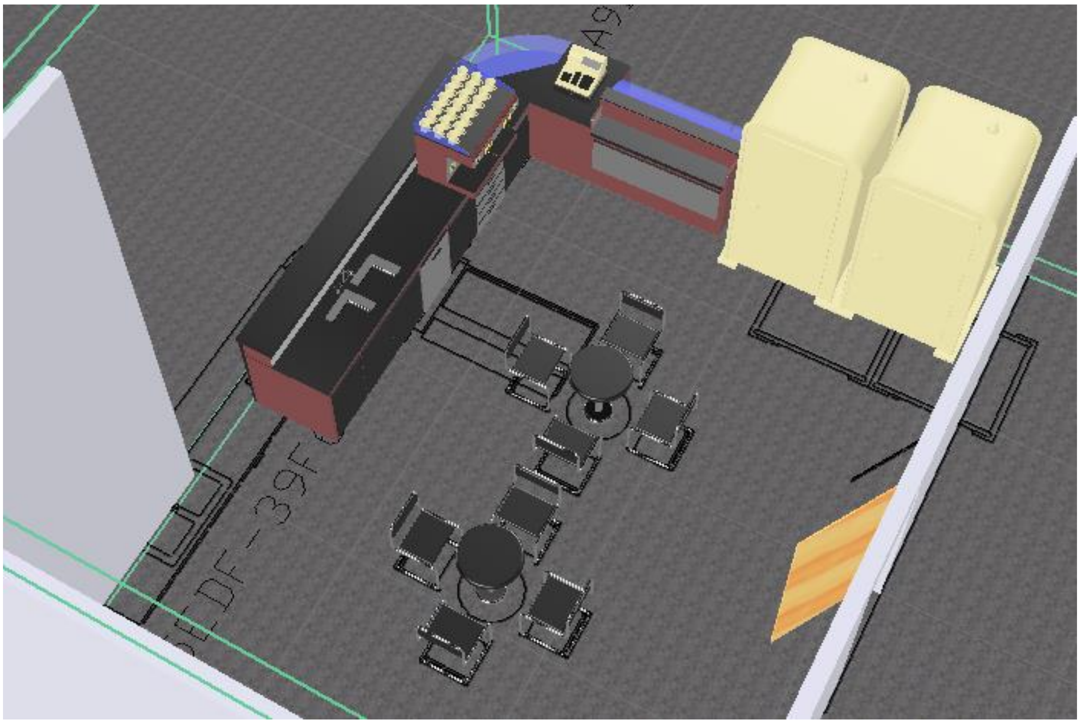


Figure 6.18. LSLP CRAFT-Layout 7 Break room

CHAPTER 7

LEAN INITIATIVES

7.1 Business operations and operational improvement initiatives

All proposed layouts significantly improve waiting times, minimize transportation, improve inventory, and minimize emissions. However, certain policies must be implemented to make the plant leaner. With the new strategically placed inventories and in/exit points, Company X should shift to a hybrid pull production system rather than a push production system. Once blow moulding is fixed, Company X will not be required to store excess empty bottles for future use. If the current blow moulding cannot be fixed a smaller piggyback blow moulding machine could be installed in parallel to eradicate the speed mismatch between the Type-2 Blow moulding machines and the rest of the assembly line. Furthermore, Floor marking as shown in Figure 7.1 should be placed to standardize the inventory placement. These floor markings will ensure that the travelling path is clear of any obstructions that could delay the production or cause excess motion.

Figure 7.1. Inventory floor marking (*Visual Solutions & Improvements - VSI.Eu*, n.d.)

It was evident from the interviews with the employees that there is a significant communication gap between upper management and lower management due to a lack of communication channel. Employees are not able to share their opinions and views on how certain process or procedures could be improved for the benefit of the workers and the plant. The shortcoming harbours silo thinking in the production facility. It is one of the most significant barriers for Company X, which it should overcome. Company X should start monthly awareness and meeting programs for the entire team to eliminate this thinking. This would ensure employees are aware that each plays a crucial role in the movement towards lean manufacturing. Lastly, such a communication channel will give a chance to the lower management to share ideas to improve current issues at the production facility.

Currently, only the upper management is aware of the daily net demands and the current production state. An e-Kanban such as the one developed by Nadia et al. l mentioned in Chapter 2, should be implemented to standardize and improve production. Figure 7.2 illustrates a commercially available Kanban box that Company X could implement. Using such a system will ensure will everyone at the facility is fully aware of the current production status, location of the stock and even inventory space available in each storage. Furthermore, an e-Kanban system can be integrated with a manufacturing execution system (MES) to predefine work schedules for the employees.

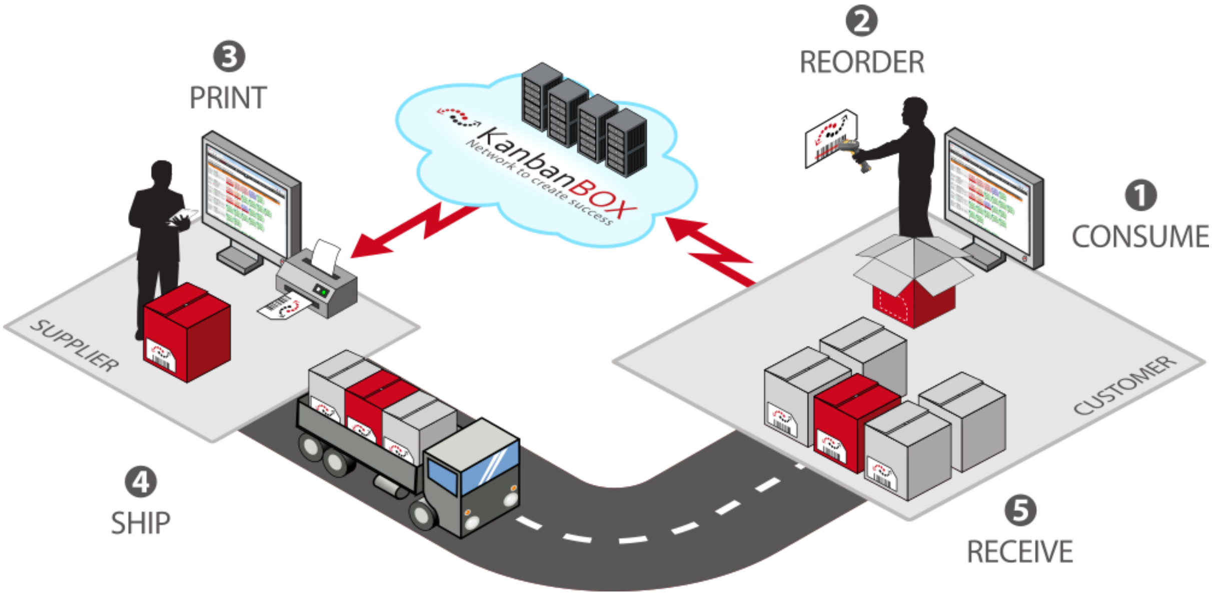


Figure 7.2. Kanban box (*KanbanBOX - Electronic Kanban (e-Kanban)*, n.d.)

Training programs and visual boards to measure the track the performance of the workers should be implemented. These training will cross-train employees to work in different departments that will minimize the use of financial resources. At the same time, performance evaluation will act as a morale boost to work better.

7.2 **Maintenance and repairs**

Currently, Company X follows a preventive maintenance schedule. In-house engineer in not fully trained for repair to maintain the equipment present at the factory. Due to this, in case of failure or breakdown, entire production comes to a halt. It is of vital importance Company X develop a TPM plan for the production facility to minimize the net downtime. Such Conditions Based Maintenance can increase the net productivity by 25% and reduce the total downtime by 75%(Gr et al., n.d.). To implement such plan it is essential that the engineer is sent for training to minimize the repair time. Furthermore, IoT enabled system could be employed to predict the health of the equipment before they occur.

Currently, tools and equipment for repairing and maintenance are placed randomly on the tool table. Due to this, a significant amount of time is spent in looking for the required tools and equipment. Shadow board, as shown in Figure 7.3 should be used to standardize the placement and minimize motion waste.

Figure 7.3. Shadow board for tools and equipment (Flexpipenic, 2021)

7.3 **Safety and Environmental Health**

Safety and Environmental Health grade can be improved by developing a safety manual and training the employees about the safety protocols that should always be followed. Currently, even though the top management is fully aware of Environmental Health and Safety (EHS) rules. However, floor men lack the knowledge of EHS. Training and awareness should be launched to create awareness in the production facility about the importance of EHS in lean philosophy. Proper ergonomic training for manual lifting of products from the production line to the pallet station will minimize back pain complaints. Furthermore, Company X needs to start keeping a ledger of near misses and accidents for future improvement. Company X has set rules for using safety gear, yet heat-resisting gloves and earmuffs are still not widely used by the employees working at the blow moulding machines. Strict enforcement policies should be placed for ensuring everyone working at the production facility is utilizing them. Obligation signs for safety equipment, should be placed throughout the facility. Figure 7.4 illustrates the safety obligation signs that should be placed at the Company X production facility.

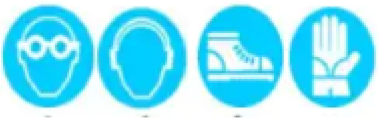


Figure 7.4. Safety equipment obligation signs

TRNC is a solar rich country. In future research, solar feasibility analysis and design should be conducted. Solar panels could be installed on the roof of the production facility. This will decrease the carbon footprint and be financially beneficial for Company X since the levelized cost of energy is considerably lower than the cost of electricity from the national grid.

7.4 **Kaizen**

As mentioned before, lean manufacturing is not a static system; its foundation is based on '*Continuous improvement,'* i.e., kaizen. Company X should aim to continuously evolve and improve the production facility and layout to reach perfection. To reach the maximum level of attainable perfection Bi-monthly meetings should be held. These meetings will ensure that all the employees, from top management to the floor worker, are accorded and that no voice is left unheard.

CHAPTER 8

CONCLUSION

8.1 LSLP Framework

Numerous studies have emphasized the advantages of employing lean layout design manufacturing practices from a social, economic, and environmental perspective; however, none of the studies demonstrate a step-by-step approach for designing a lean sustainable layout for a production facility. In order to fill the research gap, a novel Lean Systematic Layout Planning (LSLP) step-by-step approach was developed and tested for Company X purified bottled water production facility. The LSLP approached is based on the classical Systematic Layout Planning (SLP) approach and the *'Principles of Lean'* approach developed by James P. Womack and Daniel T. Jones. The six-step LSLP approach takes into account both the qualitative and quantitative data. In LSLP; GEMBA walks, value stream map, spaghetti diagrams, part family matrix, production flow matrix, process flow matrix along with Graph Theoretic Approach (GTA) construction algorithm are used to develop lean sustainable perspective layouts of the production facility. Later, Computerized Relative Allocation of Facilities Technique (CRAFT) improvement type algorithm is used to carry out pair-wise exchanges further to improve the perspective layout of the production facility. In order to overcome the limitations of the CRAFT algorithm; firstly, multiple prospective layouts of the production facility were manually generated, and later used as the input parameter for the CRAFT algorithm. Secondly, the algorithm was modified to add multiple objective functions such as the emissions produced, cost of transportation, and the total distance travelled by the goods at the production facility. After the development and selection of the final layout, various lean initiatives are looked into and recommended for the organisation.

8.2 Company X Case Study

In order to test the LSLP framework, it was applied to Company X production facility located in Nicosia TRNC. A detailed and rigorous mapping and production flow analysis of the current production facility was carried out to reach the root cause of the current inefficiencies of the production facility. The initial data provided by the company was inaccurate and outdated. Hence, majority of the data used in this research is either manually collected or based on current literature. Initial assessment of the production facility indicated excess and ill-structured transportation, which is one of the significant wastes of Company X production facility. Since it results in additional costs, congestion in flow, increased emission, excess inventory and even health and safety concerns. The final plan developed using LSLP framework reduced the total distance travelled by 35.02%, reduced the net MHD cost by 37.05%, and decreased the MHD emission by 36.86%. The LSLP framework resulted in a streamlined flow with minimized distance, lower emissions, better space utilization, improved talent utilization along with just-in-time delivery for a specific production line, which is consistent with a lean manufacturing philosophy.

8.3 Limitation and Future Work

Even though LSLP framework significantly improved the current facility layout of Company X, there are certain limitations of LSLP. Firstly, there is no certainty that the facility layout developed using LSLP framework is fully optimized and is the best solution. An exact mathematical model could be made in the future to conduct a comparative analysis of LSLP framework. Secondly, actual MHD trip costs and MHD trip emissions were not available; hence, an estimated value index was used.

This index was based on discussions with the Company Xs CEO and the literature. In the future, actual MHD costs and emissions can be calculated, and later used to validate the framework. Thirdly, a qualitative approach was used for recommending lean initiatives. In the future, a quantitative lean recommendation tool could be made to guide the organisation on which lean initiatives to apply first. Lastly, Life Cycle Analysis (LCA) can be conducted on both the current and the future manufacturing practices to assess the overall environmental impact of Company X.

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APPENDICES

A. Group technology

Table A.1. Row column masking 1st iteration

BINARY WEIGHT 2048 1024 512 256 128 64 32 16 8 4 2 1

	A	B	C	D	E	F	G	H	I	J	K	L	BINARY VALUE
1	0	0	0	0	0	0	0	0	**1**	0	0	0	8
2	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**	2341
3	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**	2341
4	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**	2341
5	0	**1**	0	0	**1**	0	0	**1**	0	0	**1**	**1**	1171
6	0	0	**1**	0	**1**	0	0	**1**	0	0	**1**	**1**	659
7	0	0	0	0	0	**1**	0	0	0	0	0	0	64

Table A.2. Row column masking 1st iteration results

	A	B	C	D	E	F	G	H	I	J	K	L
2	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**
3	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**

4	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**
5	0	**1**	0	0	**1**	0	0	**1**	0	0	**1**	**1**
6	0	0	**1**	0	**1**	0	0	**1**	0	0	**1**	**1**
7	0	0	0	0	0	**1**	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	**1**	0	0	0

Table A.3. Row column masking 2nd iteration

BINARY VALUE	112	8	4	112	12	2	112	12	1	112	12	124	
1	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	BINARY WEIGHT
2	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**	64
3	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**	32
4	**1**	0	0	**1**	0	0	**1**	0	0	**1**	0	**1**	16
5	0	**1**	0	0	**1**	0	0	**1**	0	0	**1**	**1**	8
6	0	0	**1**	0	**1**	0	0	**1**	0	0	**1**	**1**	4
7	0	0	0	0	0	**1**	0	0	0	0	0	0	2
1	0	0	0	0	0	0	0	0	**1**	0	0	0	1

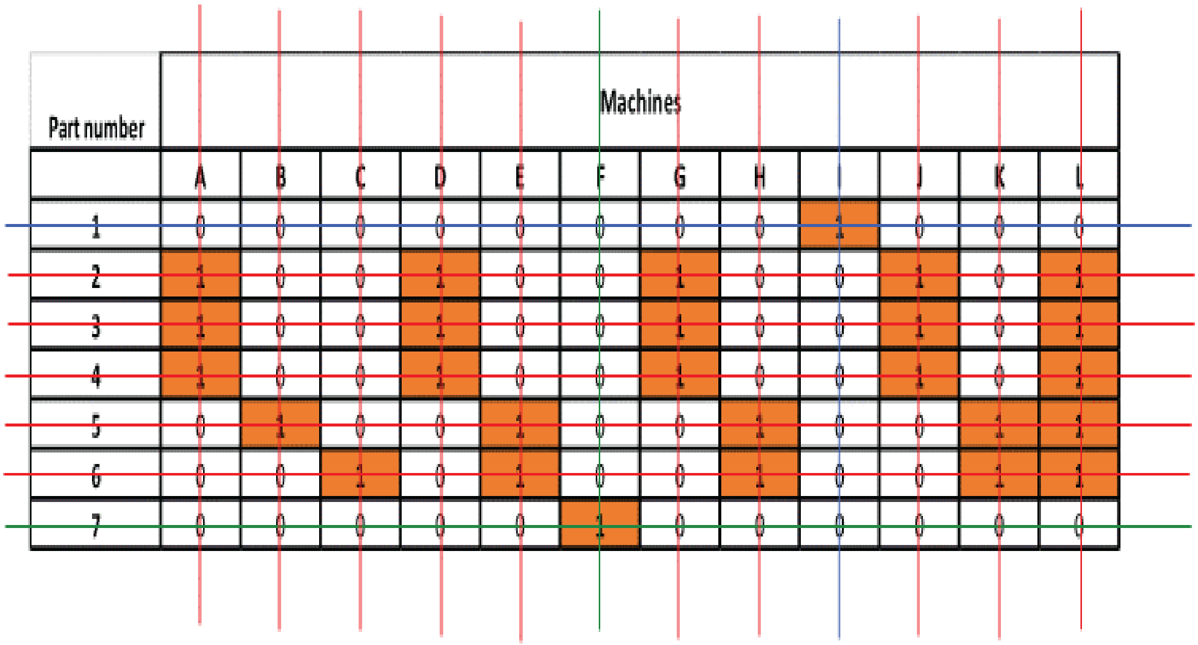
Table A.4. Row column masking 2^{nd} iteration results

1	**L**	**A**	**A**	**G**	**J**	**E**	**H**	**K**	**B**	**C**	**F**	**I**
2	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	0	0
3	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	0	0
4	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	0	0
5	**1**	0	0	0	0	**1**	**1**	**1**	**1**	0	0	0
6	**1**	0	0	0	0	**1**	**1**	**1**	0	**1**	0	0
7	0	0	0	0	0	0	0	0	0	0	**1**	0
1	0	0	0	0	0	0	0	0	0	0	0	1

Table A.5. Row column masking 3rd iteration

1	L	A	A	G	J	E	H	K	B	C	F	I
2	1	1	1	1	1	0	0	0	0	0	0	0
3	1	1	1	1	1	0	0	0	0	0	0	0
4	1	1	1	1	1	0	0	0	0	0	0	0
5	1	0	0	0	0	1	1	1	1	0	0	0
6	1	0	0	0	0	1	1	1	0	1	0	0
7	0	0	0	0	0	0	0	0	0	0	1	0

1	0	0	0	0	0	0	0	0	0	0	0	1



Part number	Machines											
	A	B	C	D	E	F	G	H	I	J	K	L
1	0	0	0	0	0	0	0	0	1	0	0	0
2	1	0	0	1	0	0	1	0	0	1	0	1
3	1	0	0	1	0	0	1	0	0	1	0	1
4	1	0	0	1	0	0	1	0	0	1	0	1
5	0	1	0	0	1	0	0	1	0	0	1	1
6	0	0	1	0	1	0	0	1	0	0	1	1
7	0	0	0	0	0	1	0	0	0	0	0	0

Figure A.1. Row column masking results

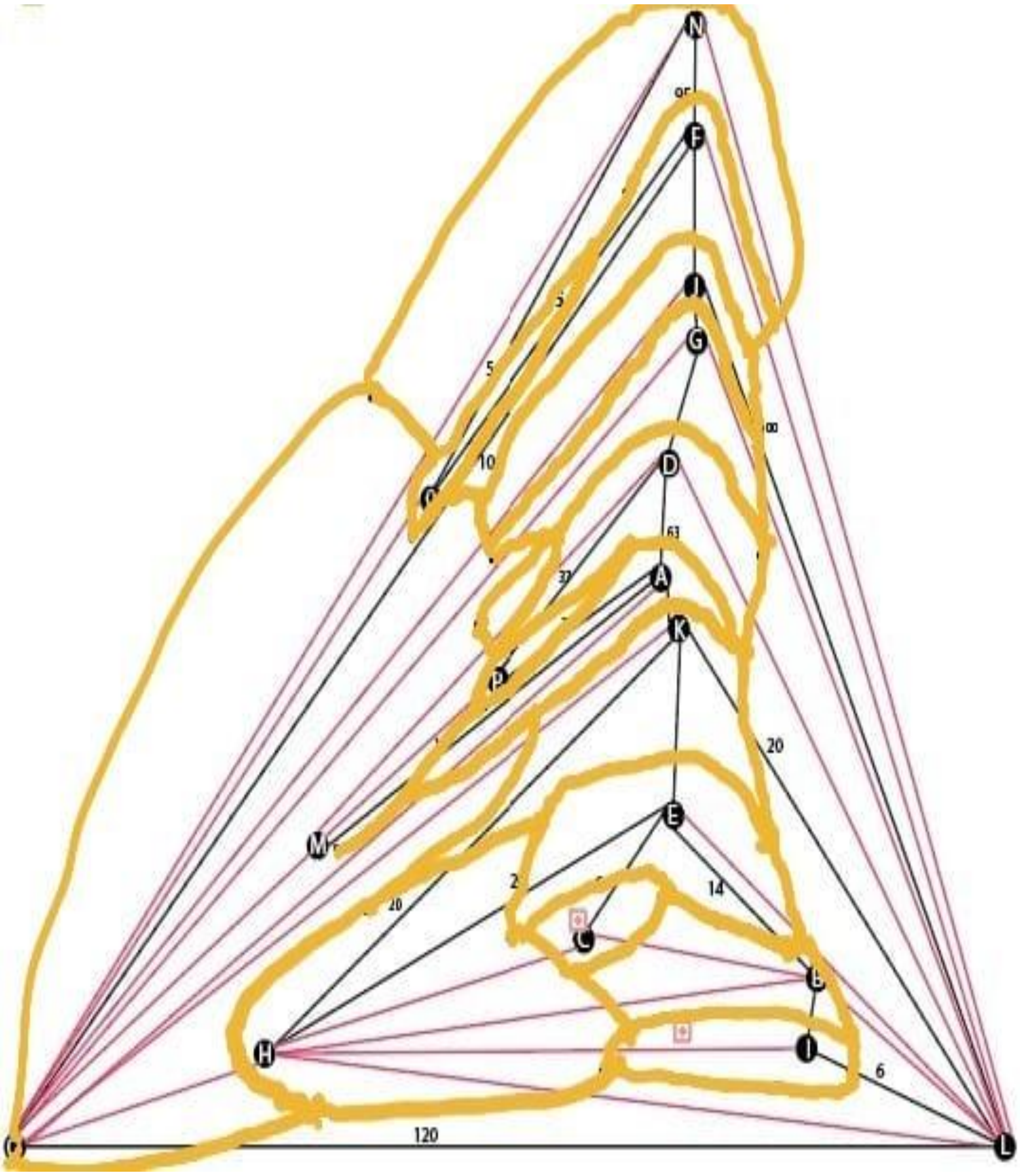


Figure A.2. Dual graph Company X

B. Estimating value index for Lean MHD costs and emission

Table B.6. MHD Cost level

Perceived Value	Description	Score
Insignificant	Dictates to Insignificant MHD cost since, the products or materials being transported are Lightweight & Low volume products e.g. preforms and caps.	1
Low	Dictates to Insignificant MHD cost since, the products or materials being transported are Light weight but have medium volume comparatively e.g. empty Type-2 and Type-3.	2
Medium	Dictates to Medium MHD cost since, the products or materials being transported have medium weight but have medium volume e.g. Finished Type-2 products	3
High	Dictates to high MHD cost since, the products or materials being transported have high weight, high volume for e.g., Finished Type-3 and Type-1 cartons.	4
Highest	Dictates to Highest MHD cost since, the products or materials being transported have Highest weight & Highest volume for e.g., Type-4 products and pelleted products	5

Table B.7. MHD Emission level

Emission Level	Description	Score
Low	Manually operated machines	1-2
Medium	Semi-automated machines and equipment	3
High	Fully Automated machines	4-5

C. CRAFT current layout

Table C.8. Craft input parameter

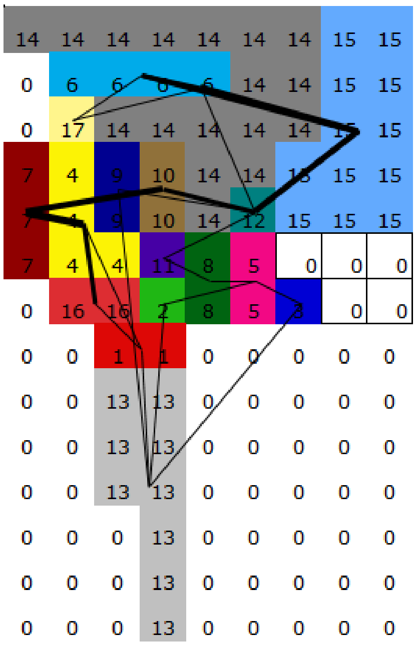
Problem Name:	Company X
Number Depts.:	17
Length(cells):	14
Width(cells):	9
Area (cells):	126

Table C.9. Current layout centroids

Department	Scale Area-cells	x-centroid	y-centroid
D 1	2	3	7,5
D 2	1	8,5	6,5
D 3	1	7,5	6,5
D 4	4	0,75	2,25
D 5	2	4,5	6
D 6	4	2	3
D 7	3	0,83333331	5,16666651
D 8	2	5,5	6
D 9	2	2	6,5
D 10	2	3	5,5
D 11	2	6,5	6
D 12	1	5,5	4,5

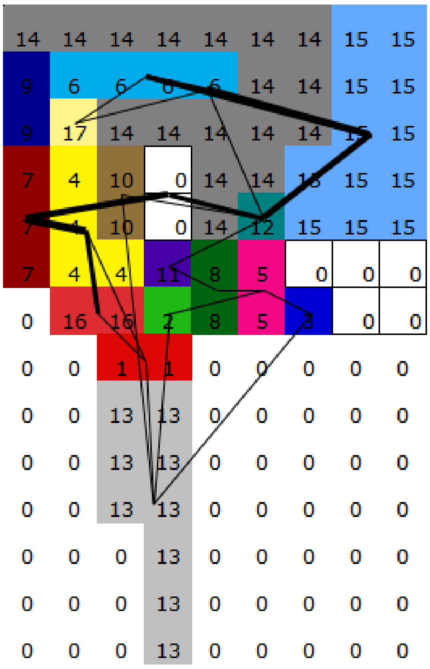
D 13	9	3,05555558	10,833333
D 14	17	7,20588255	3,20588231
D 15	12	4,41666651	0,91666669
D 16	2	3	1,5
D 17	1	3,5	6,5

D. LSLP-CRAFT Final layouts



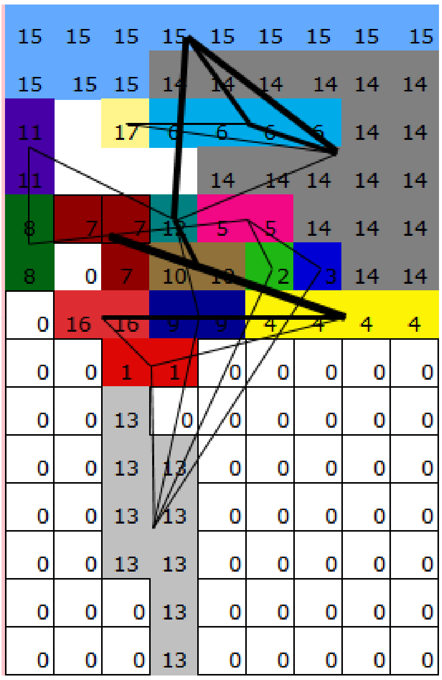
14	14	14	14	14	14	14	15	15
0	6	6	6	6	14	14	15	15
0	17	14	14	14	14	14	15	15
7	4	9	10	14	14	15	15	15
7	4	9	10	14	12	15	15	15
7	4	4	11	8	5	0	0	0
0	16	16	2	8	5	3	0	0
0	0	1	1	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.3. LSLP CRAFT-Layout 1



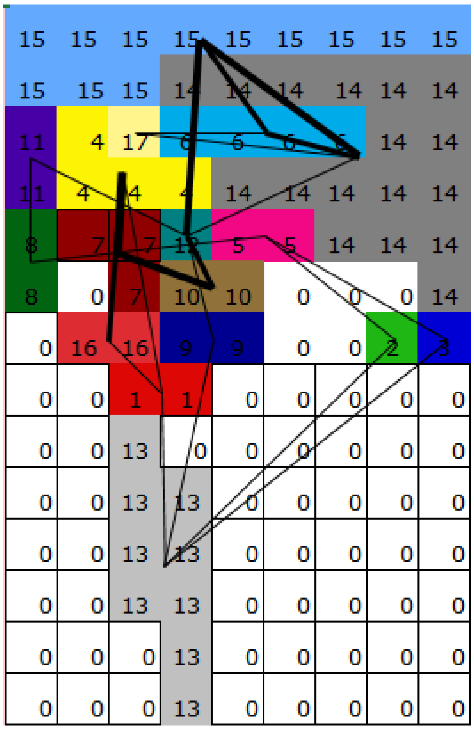
14	14	14	14	14	14	14	15	15
9	6	6	6	6	14	14	15	15
9	17	14	14	14	14	14	15	15
7	4	10	0	14	14	15	15	15
7	4	10	0	14	12	15	15	15
7	4	4	11	8	5	0	0	0
0	16	16	2	8	5	3	0	0
0	0	1	1	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.4. LSLP CRAFT-Layout 2



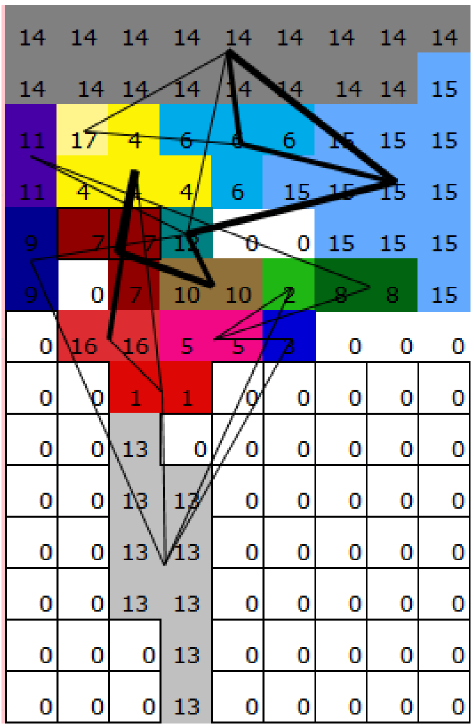
15	15	15	15	15	15	15	15	15
15	15	15	14	14	14	14	14	14
11		17	6	6	6	6	14	14
11				14	14	14	14	14
8	7	7	12	5	5	14	14	14
8	0	7	10	10	2	3	14	14
0	16	16	9	9	4	4	4	4
0	0	1	1	0	0	0	0	0
0	0	13	0	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.5. LSLP CRAFT-Layout 3



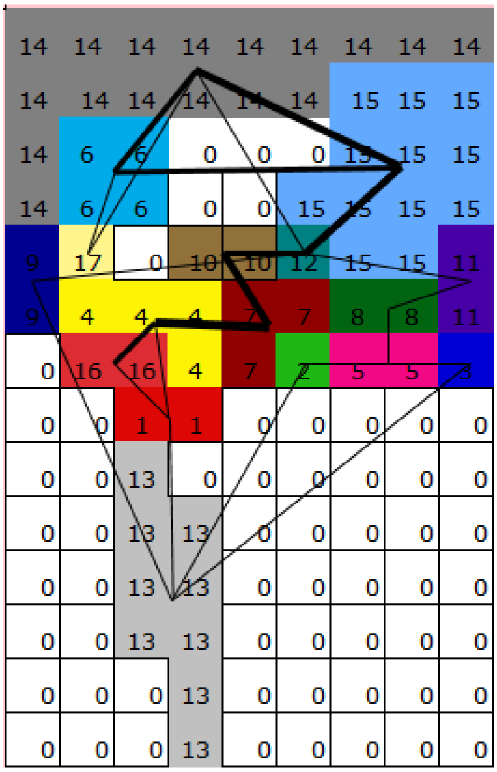
15	15	15	15	15	15	15	15	15
15	15	15	14	14	14	14	14	14
11	4	17	6	6	6	6	14	14
11	4	4	4	14	14	14	14	14
8	7	7	12	5	5	14	14	14
8	0	7	10	10	0	0	0	14
0	16	16	9	9	0	0	2	3
0	0	1	1	0	0	0	0	0
0	0	13	0	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.6. LSLP CRAFT-Layout 4



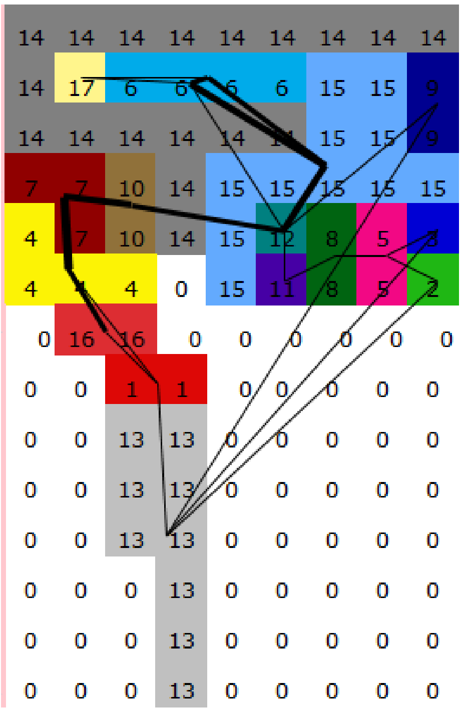
14	14	14	14	14	14	14	14	14
14	14	14	14	14	14	14	14	15
11	17	4	6	6	6	15	15	15
11	4	4	4	6	15	15	15	15
9	7	7	12	0	0	15	15	15
9	0	7	10	10	2	8	8	15
0	16	16	5	5	3	0	0	0
0	0	1	1	0	0	0	0	0
0	0	13	0	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.7. LSLP CRAFT-Layout 5



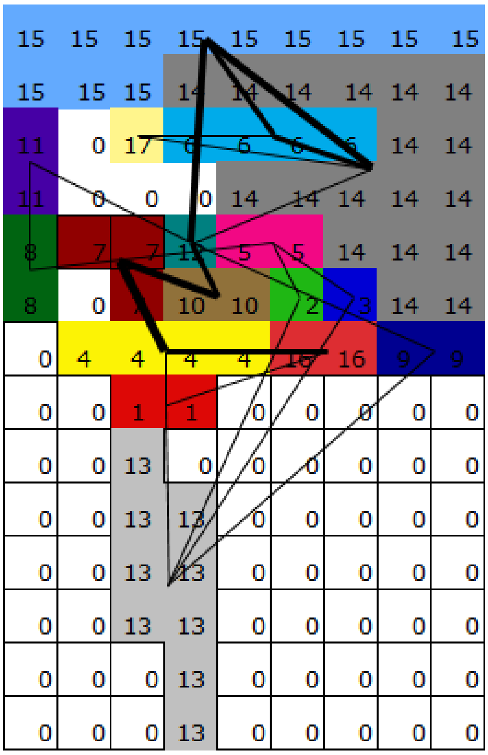
14	14	14	14	14	14	14	14	14
14	14	14	14	14	14	15	15	15
14	6	6	0	0	0	15	15	15
14	6	6	0	0	15	15	15	15
9	17	0	10	10	12	15	15	11
9	4	4	4	7	7	8	8	11
0	16	16	4	7	2	5	5	3
0	0	1	1	0	0	0	0	0
0	0	13	0	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.8. LSLP CRAFT-Layout 6



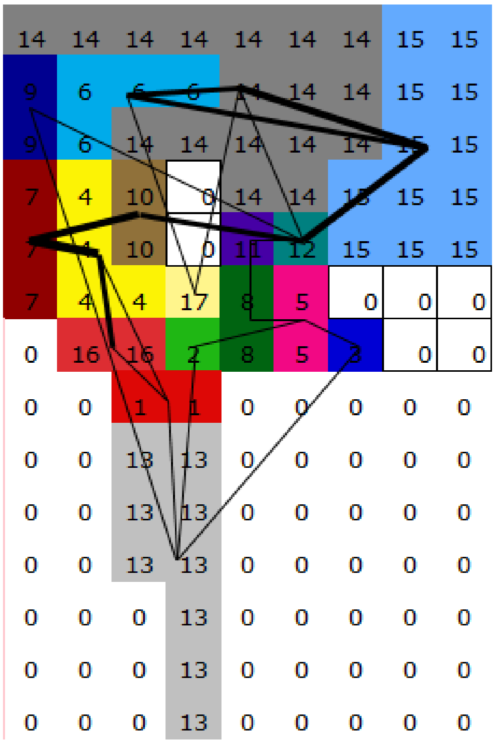
14	14	14	14	14	14	14	14	14
14	17	6	6	6	6	15	15	9
14	14	14	14	14	14	15	15	9
7	7	10	14	15	15	15	15	15
4	7	10	14	15	12	8	5	3
4	4	4	0	15	11	8	5	2
0	16	16	0	0	0	0	0	0
0	0	1	1	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.9. LSLP CRAFT-Layout 7



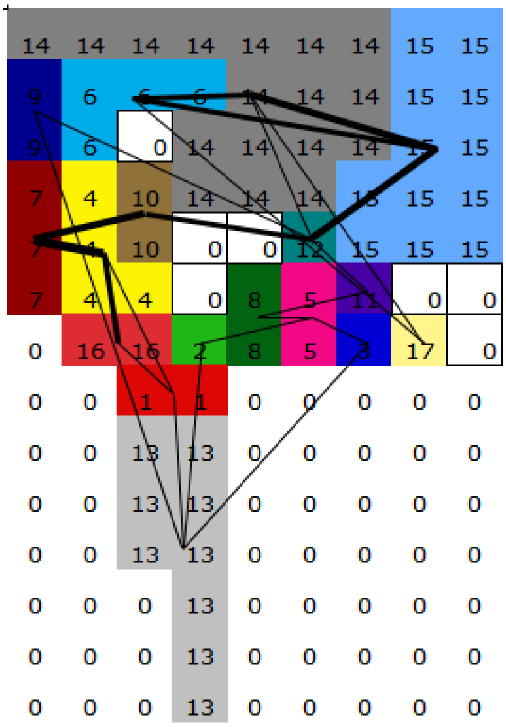
15	15	15	15	15	15	15	15	15
15	15	15	14	14	14	14	14	14
11	0	17	6	6	6	6	14	14
11	0	0	0	14	14	14	14	14
8	7	7	12	5	5	14	14	14
8	0	7	10	10	2	3	14	14
0	4	4	4	4	16	16	9	9
0	0	1	1	0	0	0	0	0
0	0	13	0	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.10. LSLP CRAFT-Layout 8



14	14	14	14	14	14	14	15	15
9	6	6	6	14	14	14	15	15
9	6	14	14	14	14	14	15	15
7	4	10	0	14	14	15	15	15
7	4	10	0	11	12	15	15	15
7	4	4	17	8	5	0	0	0
0	16	16	2	8	5	3	0	0
0	0	1	1	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.11. LSLP CRAFT-Layout 9



14	14	14	14	14	14	14	15	15
9	6	6	6	14	14	14	15	15
9	6	0	14	14	14	14	15	15
7	4	10	14	14	14	15	15	15
7	4	10	0	0	12	15	15	15
7	4	4	0	8	5	11	0	0
0	16	16	2	8	5	3	17	0
0	0	1	1	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	13	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0
0	0	0	13	0	0	0	0	0

Figure D.12. LSLP CRAFT-Layout 10